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Discover

SCIENCE FOR THE CURIOUS

May 2015

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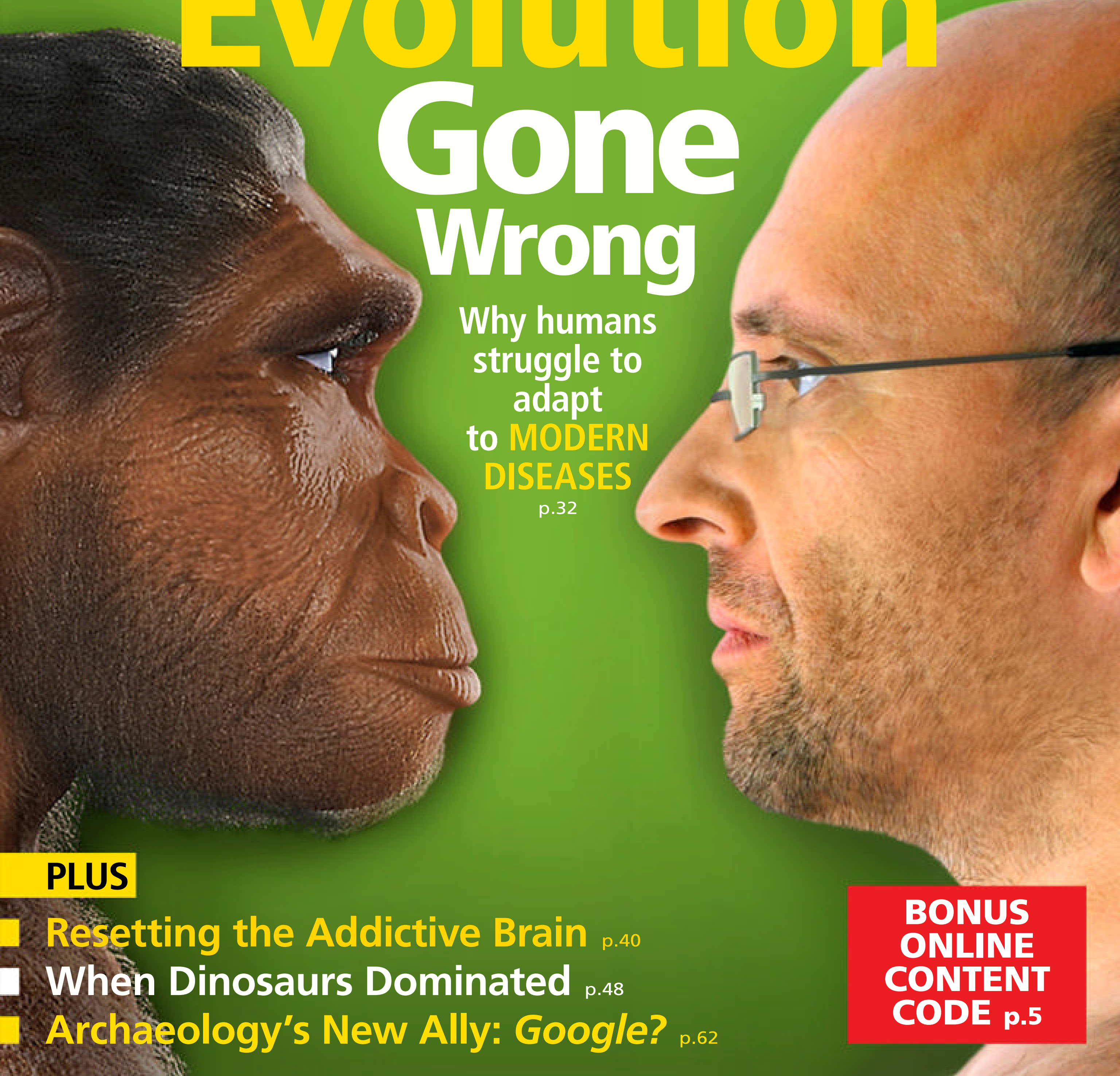

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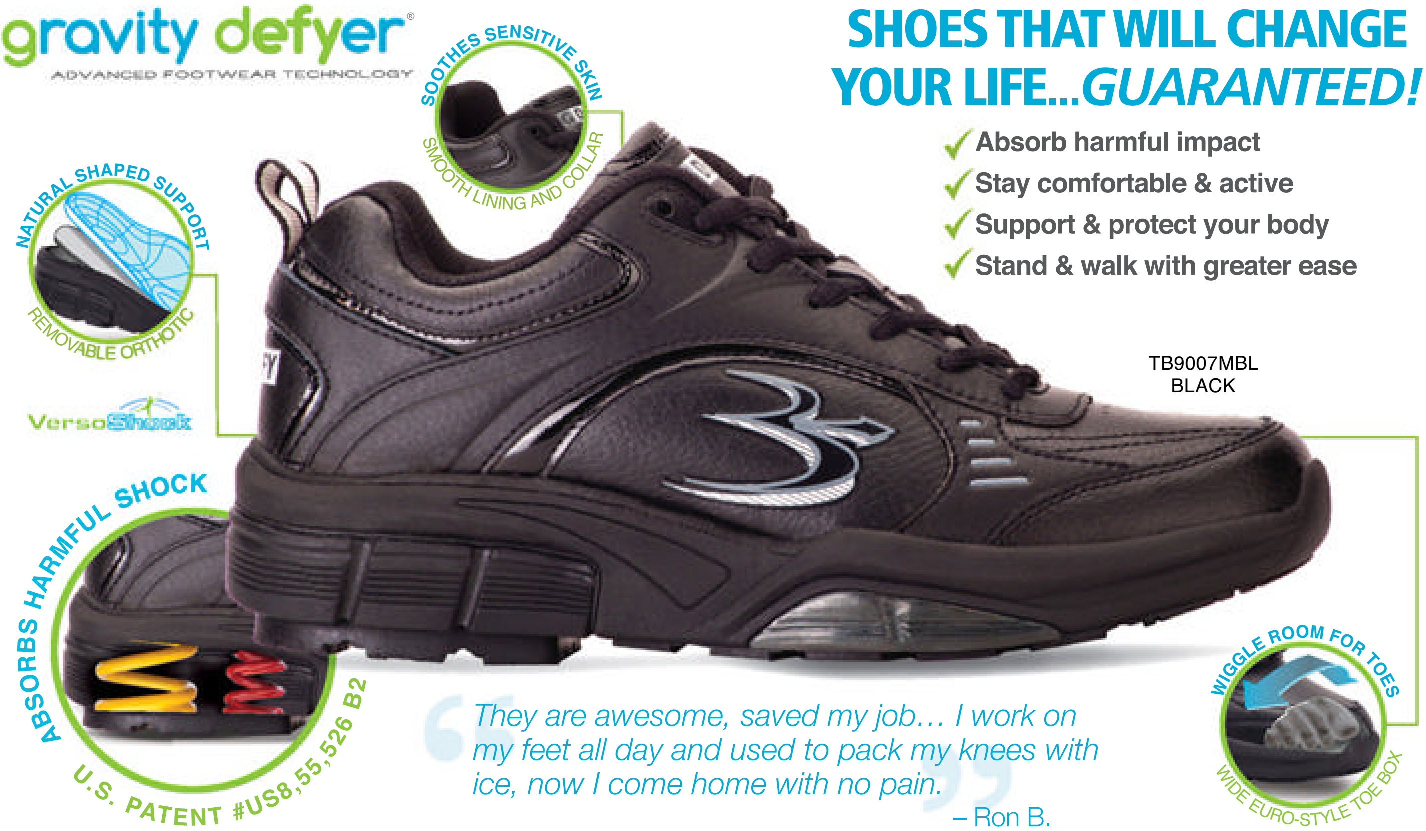

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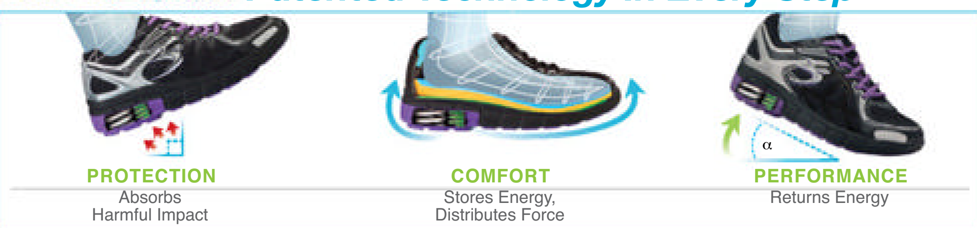

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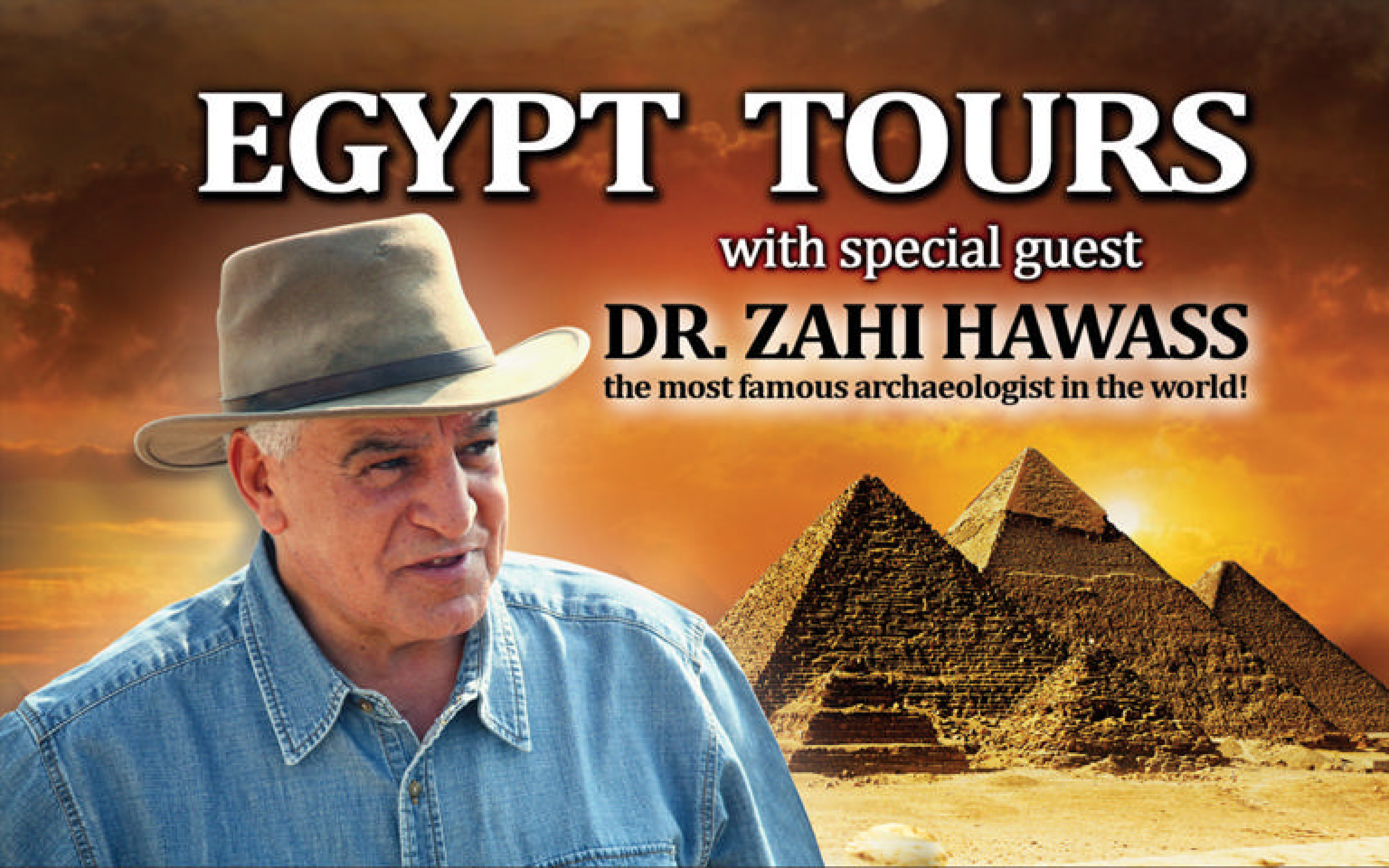

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Group photo - November 2014 Egypt tour with Dr. Zahi Hawass.

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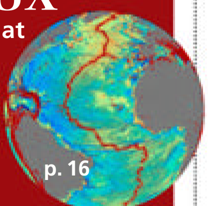

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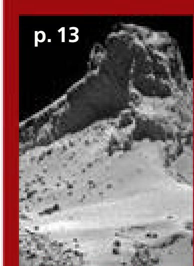

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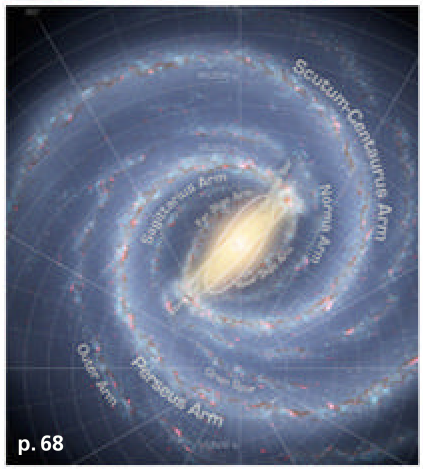

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Editor's Note

All-Time Greatest

Looking for the most amazing science stories. Ever.

It may only be spring, but here at *Discover* we've already begun to discuss plans for our biggest issue of 2016, the annual Year in Science edition, spotlighting the top 100 science stories from, well, this year.

Every year, either on this very page or online at DiscoverMagazine.com, I've asked you to share your choices for the most incredible and important science stories of the year. You're still welcome to do that, of course (although it might be a little early yet), but for the moment, let's go a little broader in scope.

What would you say are the greatest science stories *of all time*? By "greatest," I mean both the most amazing discoveries and the most epic failures — after all, history is replete with scientific breakthroughs that came from failures and mistakes.

Don't mull this one over too long. I'm more interested in the first thing that popped into your head than a more careful, considered search for the right answer. Email them to me at editorial@discovermagazine.com.

NEXT ISSUE: *Einstein said that time is an illusion, that the future is set. But this cosmologist holds a different view, which he explains in our June issue. See you then!*

Stephen C. George, **EDITOR IN CHIEF**

YOUR REPLY

In the March issue, in honor of the launch of our new Origin Story column, I asked you to tell me which period of history or human development you'd visit if you could. It was really hard to choose — so many thoughtful answers — but in the end, I went with Richard Sanders' response. He picked the same culture I would have:

OK, this is an easy one. I'd visit a civilization that invented the first mechanical computer, invented machines and steam power 2,000 years before it was repeated, whose thought and philosophy and art continue to awe and influence us to this day. And face it — the men got to wear the coolest-looking armor ever. I'd visit ancient Greece. Or the Minoan culture that inspired the tales of Atlantis.

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THE CRUX

The Latest Science News & Notes

ALASKAN LIGHT SHOW

Four rockets light up the Alaskan sky as they blast off earlier this year from NASA's Poker Flat Research Range. The photo combines four exposures taken over 30 minutes as the rockets launched into a sky filled with the northern lights and star trails. The rockets carried instruments up to about 90 miles high to collect data for research on the interaction between solar radiation and air pollution, and on how air resistance affects satellites in low Earth orbit. The two streaky white clouds of tri-methyl aluminum vapor will help reveal atmospheric turbulence patterns, which can affect orbiting satellites. —ERNIE MASTROIANNI; PHOTO BY JAMIE ADKINS/NASA

Sounds of Science

Listen to the latest applications of aural research techniques.

BY MARY HOFF

When it comes to making new discoveries, some scientists are all ears. Whether from a star's sighs or a forest's murmurings, the sound waves these researchers study tell them things their eyes could never see, providing information about the past and even the future of their varied research.

20,000 Hz The highest pitch humans can hear.

Music of the Stars

(0.00005–0.0009 hertz)

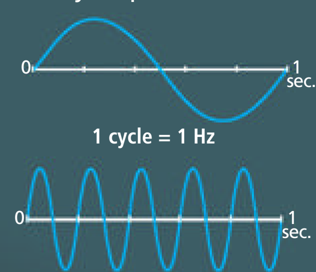
Gases dancing deep within stars create ultralow-frequency sound waves, appearing as rhythmic changes in brightness and temperature. Observing 34 young stars, an international team of astronomers learned the waves can reveal the stars' relative ages and other traits — and so provide a valuable tool to explore the evolution of the universe.

The Christmas Tree Cluster

20 Hz The lowest pitch humans can hear.

WHAT'S A HERTZ?

One sound wave, or cycle per second.



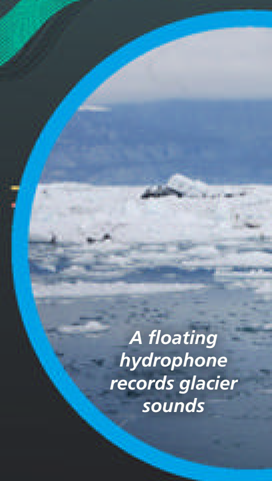
Snack Attack

(80–3,000 hertz)

It's hard to think of plants as being good listeners, but they do respond to sound waves, especially when hungry insects are involved. Researchers at the University of Missouri played a recording of munching caterpillars — and their broad range of sound waves — near the plant *Arabidopsis*, which is considered to be the lab rat of the botanical world. Plants exposed to the sound produced larger amounts of anti-insect chemicals than plants that weren't.

A recording device (upper right) picks up vibrations from a caterpillar chewing

262 Hz The tone of a piano's middle C.

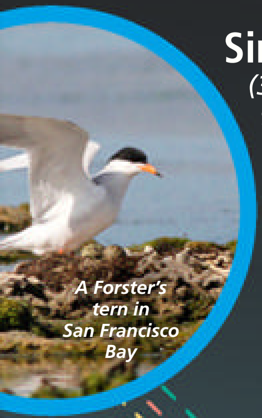


A floating hydrophone records glacier sounds

Simpler Seabird Survey

(3,000–3,500 hertz)

Seabirds are notorious for nesting in inaccessible places, frustrating efforts to monitor populations. Scientists studying Forster's terns in San Francisco Bay may have found an answer: They discovered that a colony's sound, which is much easier to gather, is enough to compare the number of nests between colonies and across years.

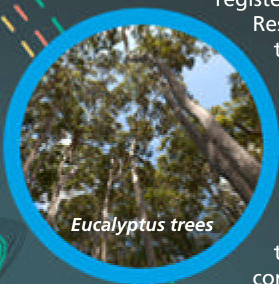


A Forster's tern in San Francisco Bay

Calls of the Wild

(1,000–11,000 hertz)

To check your health, a doctor might listen to your heart beat and lungs fill with air. It turns out sound can register a lot about the health of an ecosystem, too. Researchers in Queensland, Australia, assessed the condition of fragmented eucalyptus forests at 10 sites using conventional measures — including the size of forest patches, vegetation characteristics and the number of bird species detected — and sound recordings. They found that the more prevalent the human-generated sounds, such as traffic, machinery and voices, the poorer the ecological condition. The researchers concluded that sound can be a valuable, and relatively inexpensive, tool for assessing the ecological well-being of forest fragments.

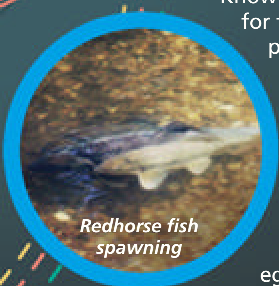


Eucalyptus trees

Hubba Hubbub

(172–15,000 hertz)

Knowing when and where fish breed is key for fish biologists who develop ways to keep populations healthy. But good luck trying to spot spawning fish in murky or fast-flowing rivers. Researchers from the University of Georgia compared visual observations of redhorse fish species in northern Georgia rivers with sound recordings to identify spawning signatures — patterns of sound waves related to the disturbance of gravel as the fish released eggs and milt. The ichthyologists found they could detect spawning activity up to 20 meters from underwater microphones.

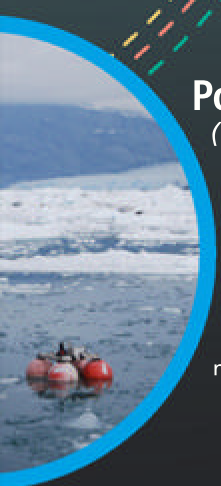


Redhorse fish spawning

Pop Goes the Glacier

(1,000–3,000 hertz)

Melting glaciers are not only sights to behold, but also are full of groans, creaks, cracks and splashes. After a glaciologist from Alaska believed she heard trapped air bubbles escaping the ice, she teamed with other scientists from Texas to eavesdrop on bits of melting glacier ice taken from Gulkana Glacier in Alaska. In the lab, the team found that the noises emanating from the ice closely correlated with observations of popping bubbles, both in timing and loudness. Such acoustic measurements of bubble-breaking can now help monitor where and how quickly glaciers are melting.



BACKGROUND: DARK INK/SHUTTERSTOCK. COUNTERCLOCKWISE FROM TOP LEFT: NASA/JPL-CALTECH/P.S. TEIXEIRA (CENTER FOR ASTROPHYSICS); ROGER MEISSEN/UNIVERSITY OF MISSOURI; JEFF NYSTUEN/UNIVERSITY OF WASHINGTON; BUD FREEMAN/GEORGIA MUSEUM OF NATURAL HISTORY; PICTUREPARTNERS/SHUTTERSTOCK; ABE BORKER/UNIVERSITY OF CALIFORNIA-SANTA CRUZ. OXYGEN ILLUSTRATION: TATIANA53/SHUTTERSTOCK

QUICK HIT

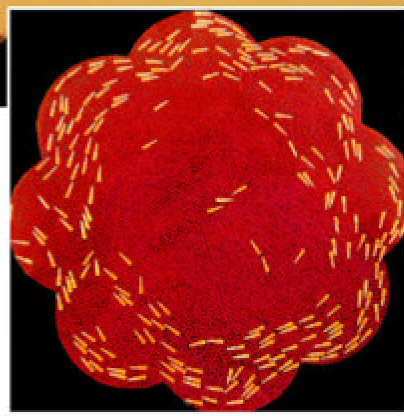
Making Oxygen Out of Thin Air

Thanks to plant photosynthesis and its byproducts, we can breathe in oxygen around us and stay alive. But before the dawn of plants, scientists thought Earth's oxygen originated from a multistep process that starts when carbon dioxide reacts to ultraviolet light. Recent findings published in the journal *Science*, though, show it's possible to get O_2 from CO_2 in just one step.

Researchers had long suspected there was an alternative to the multistep process but lacked the technology to test their hypotheses. So, armed with improved equipment, University of California, Davis researchers subjected carbon dioxide to high-energy ultraviolet light particles in a vacuum. CO_2 usually breaks down into CO and O, and then it goes through additional steps before producing breathable O_2. But since the team used higher levels of ultraviolet light than previous experiments, about 5 percent of the CO_2 turned to O_2 and C, while the rest became CO and O. Although it's a small amount, knowing O_2 can form in one step could change how we model not only our atmosphere's formation, but that of other planets.

—LEAH SHAFFER

The skillful precision required for starlings flying in a flock has emerged for the first time in an inorganic system in a lab.



A single layer of millimeter-size, tapered, brass rods aligns spontaneously on a vibrating surface amid a background of aluminium beads. The plate's flower shape helped perpetuate the flow of the rods among the beads, revealing the underlying physics.

Go With the Flow

Physicists spur flocking behavior in a lifeless system.

Birds in a flock, darting and swooping in synchrony, display skillful precision in their collective motion. Now a group of physicists has coaxed flocking behavior out of a completely lifeless system — a collection of tiny brass rods and spherical beads on a vibrating plate.

Researchers from the Indian Institute of Science in Bangalore had studied the physics of such rods for years. They focused their efforts on producing flocking after taking inspiration from research on locusts, which align in flocks only when crammed together above a certain density.

The same phenomenon, the researchers thought, might be observable with the rods. The millimeter-size rods are tapered at one end to make them "walk" in a preferred direction; like a bird or a locust, they tend not to move backward.

When the group vibrated only rods, they observed short-lived hints of flocks. But the results changed dramatically when graduate student Nitin Kumar added some beads to the mix. Kumar scattered beads and rods in a single layer on a plate that vibrated 200 times a second, and he watched in surprise as the rods began to neatly assemble, circulating endlessly.

The group constructed a computer simulation of their experiments to help reveal the underlying physics. Unlike birds or locusts, which use sight or smell to interact, the rods instead communicate through the beads. "The beads became their eyes and ears," says physicist Ajay Sood. Each reorienting rod drags beads behind it, altering their flow. Other rods align themselves to that flow, like a weather vane in the wind.

The scientists hope the results can shed light on other flocking behaviors, including the collective motions of cells in wound healing and cancer, and human stampedes in crowded venues.

— EMILY CONOVER

DID YOU KNOW? Slow down! A study of more than 1,500 healthy individuals in Denmark found that fast joggers had the same risk of death as sedentary non-joggers. Those with the lowest risk? Slow joggers who ran no more than three times a week for a weekly total of one to 2.4 hours, according to the study published in the *Journal of the American College of Cardiology*.

TOP: ANDREW BAILEY/FLPA/SCIENCE SOURCE. BOTTOM: AJAY SOOD/INDIAN INSTITUTE OF SCIENCE

DEADLYPHOTO.COM/ALAMY

A coal-fired power station belches smoke in Barentsburg, Russia. Soot from sources like this mix into the Arctic's atmosphere and can land on the Arctic ice cap, causing the darkened snow to absorb more sunlight and melt, even in winter months.

Cold War Data Reveals Soot Surprise

Environmental chemist Liaquat Husain of the University at Albany-SUNY had hit a snag on his models that tested the impact of soot on the Arctic climate. He needed more data. Luckily, when he explained his need for historical atmospheric measurements at a lecture in Helsinki, his pleas fell on the perfect sets of ears.

In the audience were researchers from the Finnish Meteorological Institute, which happens to have the longest continuous record of atmospheric Arctic soot. Since 1964, Finnish researchers — anxious about nuclear contamination from the neighboring Soviet Union — had been measuring several air pollutants, including radioactive particles and soot.

Husain and the institute's scientists found that from 1964 to 2010, soot emissions were four times higher than the predictions of the field's leading model. Even worse, most models got the timing of soot distribution wrong. "That's pretty serious," says Husain. Their findings indicated that twice as much soot was deposited on snow in winter compared with summer, meaning that the sunlight-absorbing soot likely caused greater melting of the Arctic ice cap during the winter. —LUCAS LAURSEN

INBOX

Science Starters: Chemistry Kits

Our December feature on vintage science kits brought back many happy memories for readers, and their stories continue to roll into our offices. Here's one of our favorites — so far.

Throughout the 1950s, I went to an elementary school that did not teach science. For my 12th birthday, my dad tossed a Montgomery Ward catalog at me and said, "Pick out your birthday gift!" At that time, it was unusual for a girl to choose what I did, but I picked out a tri-fold-out deluxe chemistry set equipped with microscope, test tubes, test tube holders, slides and chemicals. Two months later, one of my best friends received a chemistry set for Christmas. The two of us combined our equipment and housed ourselves in her basement, with a sign on the door that read, "MAD SCIENTISTS — BEWARE!" That kept her younger sisters out!

Both of us ended up choosing science-affiliated careers. Fast-forward 50-plus years: Two weeks ago, we reunited and excitedly took a tour of my daughter's research science lab, where she is the principal investigator. What a thrill for the both of us to see real scientific achievements being made in front of our eyes.

Dorine Gross *Rye, NH*

A Kick-Butt Way to Power Electronics

The used cigarette butts littering your city's sidewalks could serve as an energy storage material for anything from smartphones to wind turbines. South Korean chemical engineers successfully converted used cigarette filters into a type of porous carbon ideal for conducting electricity.

Minzae Lee and team subjected the filters to a high-temperature process called pyrolysis, transforming the organic materials inside them into a porous carbon substance. Then they applied the carbon to the surface of electrode materials used in supercapacitors, devices that store and deliver energy more quickly and more powerfully than a typical battery.

The porous carbon performed better as conductive electrode material than conventional carbon sources, often heat-treated coconut shells, coal or wood. There's no word yet on a real-world pilot program, but we hope researchers aren't just blowing smoke about its potential. —LEAH SHAFFER

BOOKS

PROFESSOR STEWART'S INCREDIBLE NUMBERS

By Ian Stewart

It's hard to square — no pun intended — our technologically advanced world with widespread math phobia. Numbers power our lives like never before, yet many people find a trip to the dentist preferable to wrestling with an equation. Enter emeritus math professor Stewart. With a chatty tone and sizable wit, he introduces numbers more as beloved sitcom characters than concepts that puzzle and perplex. Full of history, pop culture references and real-world examples, Stewart's ode to the odds and evens infects the reader with his own self-described "enchantment" by numbers. —GEMMA TARLACH

BEYOND: OUR FUTURE IN SPACE

By Chris Impey

To understand the current, mostly privately funded space race, University of Arizona astronomer Impey begins by looking back. Way back. Drawing a parallel to the first modern humans to leave Africa, Impey casts space exploration and colonization as inevitable for our insatiably curious species. That philosophical undercurrent continues through lively discourses on space tourism, early rocket science, alternate reality, the multiverse and more. —GT

THE THRILLING ADVENTURES OF LOVELACE AND BABBAGE

By Sydney Padua

A heady mix of alternative history, adventure and lots and lots of footnotes, this graphic novel follows two almost-heroes through a parallel universe, fighting crime and restoring order with their 1830s steam-powered computer. In reality, mathematician Charles Babbage never finished the machine, and Ada, Countess of Lovelace, never saw her ingenious computer programs brought to life. But that doesn't stop film animator Padua, who blends fanciful situations, mathematical truths and a heap of historical facts to create an outlandish, enlightening tale. —BRENDA POPPY

INFESTED

By Brooke Borel

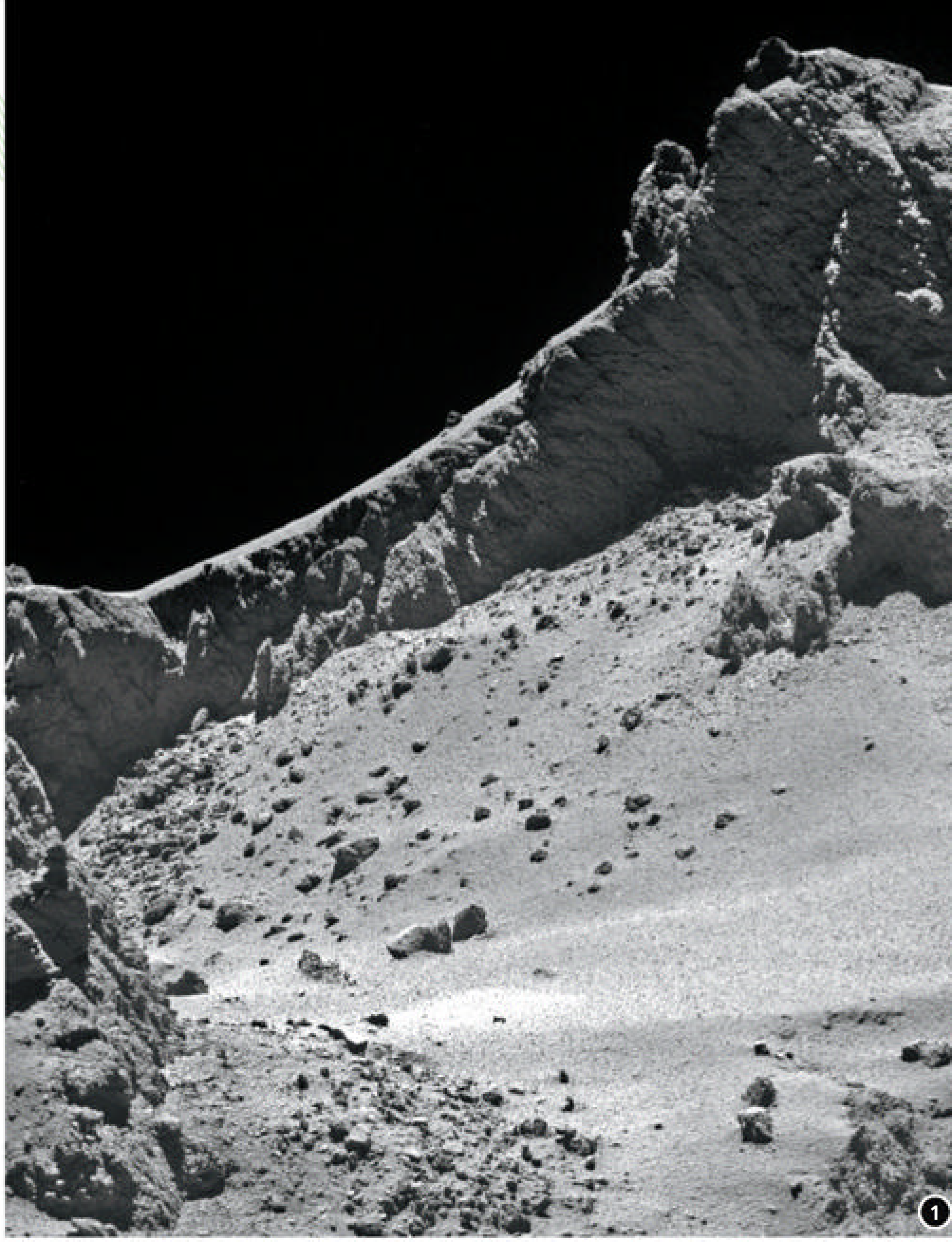
Bed bugs have overstayed their welcome by millennia, and journalist Borel explains why with an up-close look at how these bloodsuckers evolve and develop resistance to our myriad methods of extermination. From scientists who feed their own blood to colonies of bed bugs (just to learn how to kill them) to extreme measures such as dousing the critters with DDT or setting mattresses ablaze, we'll do anything for clean sheets. But we won't win, says Borel, as bed bugs wriggle into the fabric of our economies, cultures and collective psyche. —CARL ENGELKING

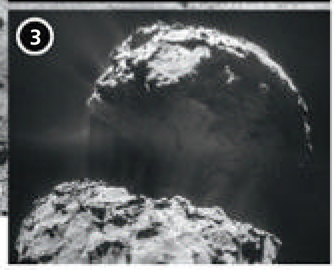
THE REAL DOCTOR WILL SEE YOU SHORTLY

By Matt McCarthy

They may seem superhuman sometimes, but doctors are people, too. McCarthy gives readers a brutally honest, often darkly comical glimpse into the formative days of his medical career. Teeming with tales of transformative mentorships and patient-doctor bonds, close calls and McCarthy's own life-threatening medical mishap, *The Real Doctor* is an enthralling account of the metamorphosis of an uncertain medical resident into a skilled physician. —LACY SCHLEY

ROMAN SIGAEV/SHUTTERSTOCK





Up Close With a Comet

Its lander may be kaput, but the Rosetta mission is still kicking strong.

After not quite sticking the landing on its 4 billion-mile journey to Comet 67P/Churyumov-Gerasimenko last November, the Philae lander managed to complete its primary science mission in just 64 hours before losing power. It conducted all the planned experiments and sent the data to Earth, including the first images ever taken from a comet's surface. The lander is now powerless because its solar panels are lying in shadow, but the obstructions might melt as the comet nears the sun, allowing Philae to return to life.

Meanwhile, the Rosetta probe orbiting the comet has been busy, revealing a striking array of surface features on Churyumov-Gerasimenko's two-lobed nucleus. A surprising discovery: The water vapor emissions from the comet are significantly different from the stores on our planet, suggesting that asteroids, not comets, may have been the main source of Earth's water.

Astronomers also have seen the comet release "fluffy" dust particles rich in sodium and lacking in ice. These particles probably collected on the comet's surface after its previous close swing by the sun six-and-a-half years ago. The team soon hopes to observe a new type of particle as the comet sheds its fluffy dust layers.

Rosetta will witness this and other changes as Churyumov-Gerasimenko stalks the sun — its closest approach hits in August — and then leaves. —BRIAN JONES

1. Rosetta's camera captures one of two lobes of comet 67P/Churyumov-Gerasimenko.
2. The Philae lander deploys its three legs and antenna.
3. A mosaic made of four images taken nearly 20 miles from the comet's center.
4. The Philae lander snaps a selfie on the comet's surface.

FROM TOP: ESA/ROSETTA/MPS FOR OSIRIS TEAM MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA (2); ESA/ROSETTA/NAVCAM – CC BY-SA IGO 3.0; ESA/ROSETTA/PHILAE/CIVA

Hitching a Ride

Missed connections and lost bags might not be your biggest worry when traveling. Researchers have found that nasty, contagious bacteria can last for days on airplane surfaces.

James Barbaree, a pathologist at Alabama's Auburn University, and colleague Kiril Vaglenov were curious about how long bacteria could last under typical air travel conditions. They applied smears of methicillin-resistant *Staphylococcus aureus* (MRSA) and the virulent *E. coli* strain O157:H7 to six airplane surface types — armrests, plastic tray tables, metal toilet buttons, window shades, seat pocket cloths and leather — which were supplied by an unnamed major airline.

What they found was disturbing. MRSA lasted for 168 hours, or seven days, on seat pockets (where travelers reach for magazines and store their iPads), while *E. coli* samples thrived for up to four days on armrests. Barbaree and Vaglenov rubbed pig skin on the tainted surfaces to mimic contact with human flesh. They found that the less porous the surface, the more transmissible the bug.

Bacteria survived longer, however, on more porous surfaces, such as seat pockets, though they were much less transmissible than those on, say, a tray table.

The researchers are now performing the same tests on *Streptococcus pyogenes,* which causes strep throat. They also are testing cleaning agents that might help prevent bacterial stowaways.

For now, Barbaree says regular hand-washing is probably the best way to prevent the spread of disease. He says he and his wife now take alcohol wipes with them on flights.

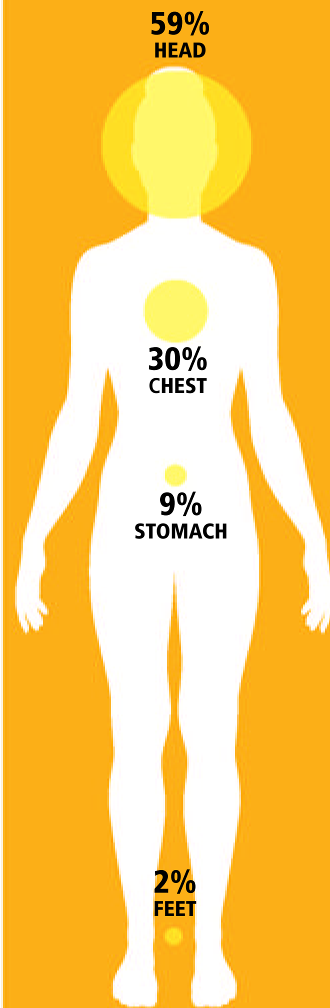
And the next time you're waiting to get on a plane, ponder this: There are no federal cabin-cleaning regulations.

— SUSANNE RUST

WEB

Express Your 'Self'

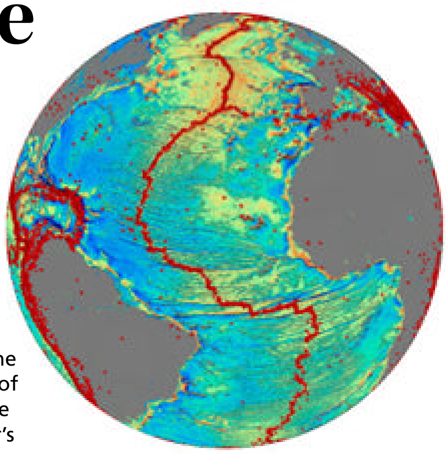
Our December Mind Over Matter article, " 'I' Marks the Spot," explored the question: Where in the body does your "self" reside? Answers in published studies vary, but the greatest percentage of responses usually puts the self somewhere around the eyes. We asked Discover *readers to weigh in online, and here's what you told us.*



Where are you? Take our "I" spot quiz at **Discovermagazine .com/Ispot**

PLANE: MY GOOD IMAGES/SHUTTERSTOCK. BACTERIA FROM LEFT: NATIONAL INSTITUTE OF ALLERGY AND INFECTIOUS DISEASES; CDC/JANICE HANEY CARR; CDC/MELISSA BROWER. SELF: DAN BISHOP/DISCOVER AND VECTOR GODDESS/SHUTTERSTOCK

Satellites Map Out Seafloor as Never Before



A gravity model of the Atlantic Ocean shows earthquakes over 30 years (red) and details of the seafloor's tectonic features.

What flies above has radically changed our knowledge of what lies beneath. New maps of Earth's seafloors derived from satellite data have identified thousands of previously unknown seamounts, faults and other tectonic features.

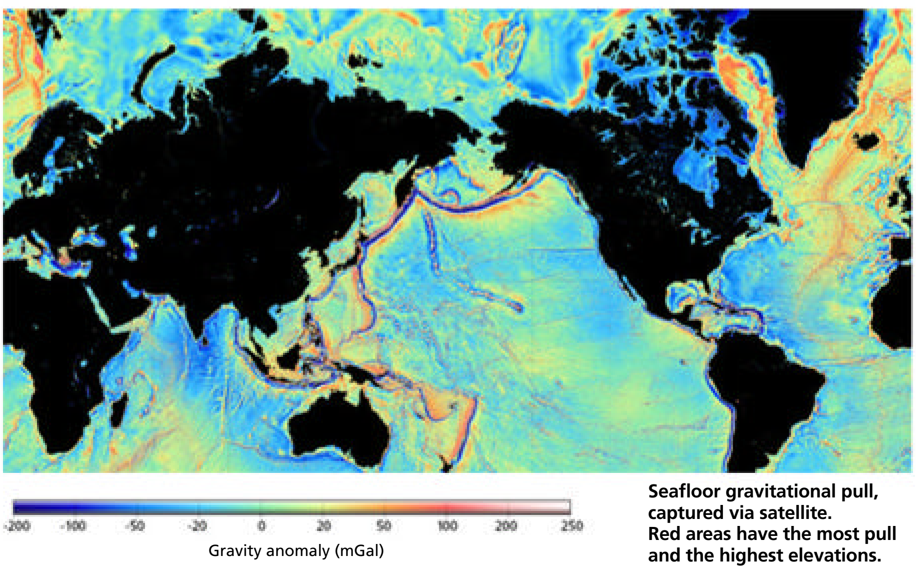
Researchers at Scripps Institution of Oceanography at the University of California, San Diego, created the maps by analyzing untapped data streams from NASA's Jason satellite and the European Space Agency's CryoSat-2 satellite. Unlike traditional shipboard sonar measurements — which bounce waves off the seafloor and have mapped out a mere 20 percent of the planet's oceans — the satellites captured subtle variations in Earth's gravitational pull at the water's surface. The variations are caused by geologic features sometimes thousands of feet below the waves and even buried beneath thick sediment.

Scripps geophysicist David Sandwell and his team developed an algorithm to crunch the data, accounting for ocean waves and tides. Their new maps will assist submarine navigation and oil exploration, but they also provide crucial new information for researchers studying plate tectonics.

Published in *Science* in October, the open-source maps also have been incorporated into Google Earth. Sandwell's team plans to release updated maps as early as this year.

Says Sandwell: "We keep dialing more data in, making it incrementally better."

— GEMMA TARLACH



Seafloor gravitational pull, captured via satellite.
Red areas have the most pull and the highest elevations.

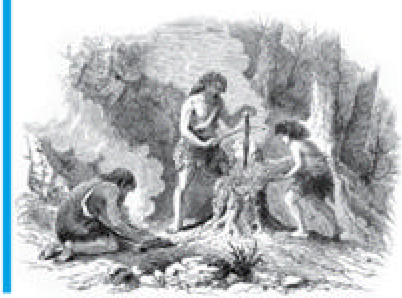
QUICK HIT

Humanity's First Social Spark

Control of fire changed everything. Harnessing this primordial energy source as early as a million years ago was a major milestone in human evolution. In a recent paper, University of Utah's Polly Wiessner proposed that, in addition to cooking food and providing warmth, fire also sparked the first social revolution.

Wiessner, who documented day and night conversations among the foraging Ju/'hoansi people of the Kalahari over a 40-year span, says evening fires extended the usable period of each day. Our first artificial light also created a perfect opportunity for storytelling, what she called "[one of] the original social media." Those early hearths became the birthplace of language, kinship and myth — elementary building blocks of culture.

— HILLARY WATERMAN



DID YOU KNOW?

An international team of scientists working in Italy announced they've cooled a vending machine-size chamber down to 6 millikelvins (minus 459.659 degrees Fahrenheit, or minus 273.144 degrees Celsius). "Nothing in the universe this large has ever been as cold," says Yury Kolomensky, a physicist at the University of California, Berkeley. Now that's pretty cool.

SEAFLOOR MAPS: DAVID SANDWELL/SCRIPPS INSTITUTION OF OCEANOGRAPHY, UC-SAN DIEGO. FIRE: GRANGER, NYC

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Unlike comparable U.S., Canadian, and other world silver coins whose designs don't change, each years' China Silver Panda features a new, one-year-only design. This leads many to seek out each and every year for their beauty and collectability. The new 2015 design is actually a 'throwback' to designs from the early 1980s which did not show the weight or fineness directly on the coin's surface. No matter what future Panda designs look like, the 2015 coin is likely to be a key date "must-have" from this popular series!

The China Silver Rush is ON!

Millions of China's prosperous new middle class buyers have flooded into the market over the past decade. They are snatching up silver coins from all around the world—but their own Silver Pandas are by far the most popular. Last year's Silver Panda coins completely sold out at the mint by October, so there is huge pent up demand for these brand new 2015 Silver Pandas!

Current prices for past-year Pandas:

Due to low availability and high demand, some past-year One Ounce BU Silver Pandas command impressive values these days:

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2002 Silver Panda	$155.20
2003 Silver Panda	$186.25
2007 Silver Panda	$103.49

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Into the Dark

A microbiologist goes deep underground to explore what happens in the absence of radiation.

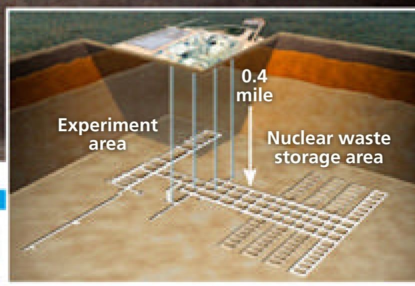
To investigate how life reacts to a nearly complete lack of radiation, astrophysicists and biologists have turned to, of all places, the same deep underground tunnels that house radioactive waste. It turns out that the thousands of feet of solid salt deposits and clay designed to protect against radiation leaks also protect the caverns from the background radiation constantly hitting Earth's surface.

That means New Mexico State University microbiologist Geoffrey Battle Smith has spent most summers commuting to work in a bumpy, 500-feet-a-minute elevator down a 2,150-foot mine shaft in the desert outside Carlsbad, N.M. Inside a tunnel, formally known as a drift, Smith incubates bacteria and mammalian cells in a steel vault the size of a garden shed.

Data from his experiments suggest the absence of background levels of radiation causes a stress response and inhibits microbial growth, challenging nuclear safety protocols that consider no radiation the only safe level of exposure.

Early in his experiments, when the 1,500-pound doors of his vault dangerously pinched an electrical cord, Smith showed how far he was willing to go to save his data.

Mine shafts at New Mexico's Waste Isolation Pilot Plant are carved into solid salt deep underground, blocking radiation from going in or out.



A small area for scientific research is set up on the north end of the plant's nearly mile-wide matrix of tunnels.

IN HIS OWN WORDS

It's 2009, and I'd just completed my mine safety training. I go underground and get to my steel vault, and there's a note saying, "We are going to shut this experiment down by tomorrow if you do not get this repair done on the vault." There's a big staff of engineers topside, so I go back up and spend the afternoon asking for help. An engineer tells me he can't do it until next week, but he says, "If you want, you can do it yourself." He gives me instructions.

When I get to the shaft I normally go down, it's closed, so I go to another one. They told me, "We'll take you down, but there's limited time. Our last manned trip is at 3:30. You've got one hour." Then I realize I don't know where I am, so I ask the hoist man, "Which way is north?" Those kinds of questions confirm that I'm not a miner.

He says, "You go down this drift, and then you make a left. Go through the air lock."

I get down there, and it's a hike. The feeling I have is that I'm on a spacewalk and I've been assigned to make a critical repair, like in the movie *Gravity*. It felt like I was in space. It was pitch black.

Geoffrey Battle Smith in a tunnel near his lab.

I'm hoping this is the right direction. My heart's in my throat. I'm going in and saving my experiment.

I get to the first unfamiliar air lock, and this huge, loud sound goes off, and this strobe turns on and scares the snot out of me. The maw of this room opens. I have to walk through this monster and then pull a rope to close it.

I didn't want to do it, but I did. I felt like I was closing myself in, thinking, "That's going to be last they heard of me."

Finally, I make it to the steel vault. I get in there and get to work. I had to hoof it to get out of there by 3:30, but I did it. I had this feeling of being fearless but actually being full of fear. It was intense.

Normally, the glare and heat of the sun is a shock coming up from underground, but in this case it was a breath of fresh air. —AS TOLD TO PETER ANDREY SMITH

FROM TOP: MICHAEL STRAVATO/THE NEW YORK TIMES/REDUX; WIPP/U.S. DEPARTMENT OF ENERGY; TANA SAUL, COURTESY OF GEOFFREY BATTLE SMITH

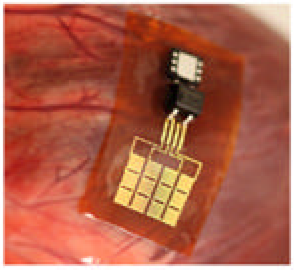
STARS OVER ANTIQUITY
Whoever made these ancient petroglyphs on a volcanic slab in California's Owens Valley finished the job more than 1,000 years ago. The significance of the symbols remains as much a mystery as the identity of the artists, who left behind no supporting oral or written history. Photographer Sean Goebel captured this 15-minute exposure under a starry sky last year. The brightest star left of center is Vega, and the stationary star at right is Polaris, also known as the North Star. —ERNIE MASTROIANNI; PHOTO BY SEAN GOEBEL

The Body Electric

Researchers have long sought to harvest renewable energy from the world around us. Now, scientists are turning inward. The beating of our hearts, the rush of our blood and the myriad chemical reactions that keep us alive are all potential energy sources. Experts are working to develop technologies that take advantage of the powerful biological ecosystems we already carry around with us.

THE POWER OF THE HEART

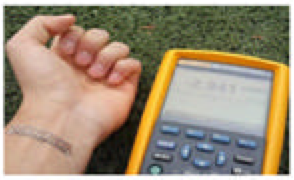
Engineers at the University of Illinois at Urbana-Champaign and Northwestern University teamed up with cardiologists at the University of Arizona to develop what they call piezoelectric nanoribbons, which attach to the outside of the heart muscle, much like a Band-Aid. These tiny strips contain crystals that create an electric current when flexed — each time the heart expands and contracts. In animal tests, electrical output reached 0.2 microwatts per square centimeter, potentially strong enough to power self-contained pacemakers and make battery-replacement surgeries a thing of the past.



This heart-powered battery harnesses electrical currents from an animal's heartbeats.

HOT TECH

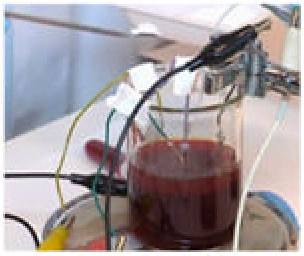
With an average temperature of 98.6 degrees Fahrenheit, the human body constantly emits heat. A research team at Korea's KAIST University used a screen-printing technique to create a flexible glass fabric wristband that turns this thermal energy into electricity. It produces about 40 milliwatts of energy from a band measuring 10 centimeters by 10 centimeters, which could trickle out a charge to keep a cellphone or smart-watch battery charged.



A multimeter measures the power output of this thermally charged wristband generator.

BLOOD BATTERY

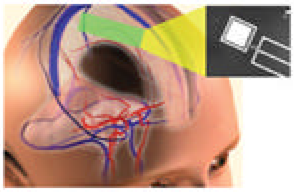
Two biomedical scientists at the University of Malmo in Sweden created an electric current between two electrodes placed in a solution of blood and water. Through a chemical process known as reduction/oxidation, one electrode steals electrons from glucose, the natural sugar in the blood, and becomes an anode, which releases electrons. The other electrode becomes a cathode, which gathers electrons, in this case, from oxygen, effectively making the system a blood-fueled battery. While it's still a concept in the lab, this biofuel cell could one day work inside the body to indefinitely power pacemakers, the researchers say.



Electrodes extract electrical energy from the glucose and oxygen in this mixture of blood and water.

RUNNING ON SUGAR

Our cerebrospinal fluid, the shock-absorbing liquid around the brain and spinal cord, is rich in glucose. Some innovators want to use that glucose the same way our bodies do — to create energy. A silicon fuel cell, which creates electricity from chemical reactions, has a platinum anode that strips electrons from glucose to create energy. The electrons then flow to a cathode, creating an electric current between the two. The researchers, based at MIT, aim to eventually embed the device in the brain to power implants that could help paralyzed patients regain limb use. —MICHAEL FRANCO



A rendering of where a fuel cell, powered by glucose in brain fluid, might be implanted.

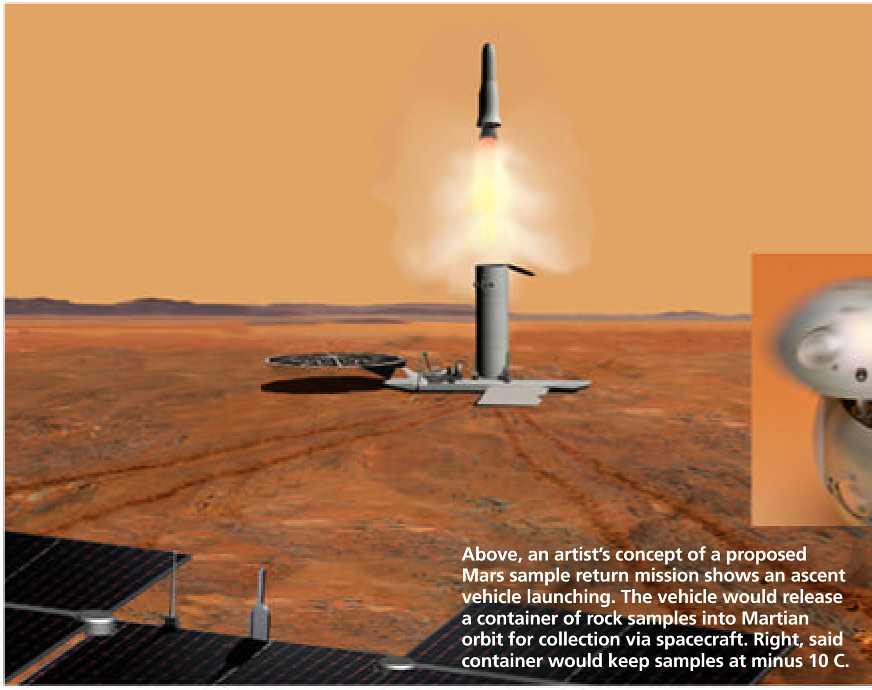
FROM TOP: UNIVERSITY OF ILLINOIS AND UNIVERSITY OF ARIZONA; BYUNG JIN CHO/KAIST; REUTERS; MENINGES AND VASCULAR ANATOMY/COURTESY OF THE CENTRAL NERVOUS SYSTEM VISUAL PERSPECTIVES PROJECT, KAROLINSKA INSTITUTET AND STANFORD/PLOS ONE/JUNE 2012/VOLUME 7/ISSUE 6/E38436

THE CRUX ReDISCOVER

Bring Home the Goods

How Earth is preparing to safely study samples from the Red Planet.

March 2003



Above, an artist's concept of a proposed Mars sample return mission shows an ascent vehicle launching. The vehicle would release a container of rock samples into Martian orbit for collection via spacecraft. Right, said container would keep samples at minus 10 C.

***Discover* reported 12 years ago** that Earthlings weren't yet ready to receive and study samples of Martian rock or soil that might contain alien life-forms. ("Are We Ready for Alien Organisms?" March 2003.) At the time, researchers didn't know the best way to combine biological containment and clean-room technology in a way that would allow them to examine samples safely without contaminating them.

The bad news is such labs still aren't ready, says Carlton Allen, a NASA astromaterials curator. The good news: Space agencies have made notable advances toward helping the world prepare.

NASA's facility designs still largely resemble labs in which researchers study Earth's most lethal pathogens. Pressurized areas restrict organisms' movement, while anything coming in or going out of the lab is sterilized. NASA relies heavily on heat sterilization, but techniques are always improving. In particular, the agency has approved the use of vaporized hydrogen peroxide to sterilize equipment, a technique that helps decontaminate medical labs and instruments and could be applied in sample receiving facilities. The vapor is effective against a wide range of microorganisms, sterilizes quickly and, unlike dry heat sterilization, won't damage most touchy electronics.

In 1971, aerospace technologist Daniel Anderson safely examines a lunar rock sample collected from the Apollo 14 mission.

NASA also is considering removing people from the lab entirely, replacing them with remotely controlled robots. "We asked a company to come up with an all-robot design to understand if we can take humans out of direct contact completely," Allen says. It turns out they can. Once NASA finalizes plans for a Mars sample-return mission, the agency plans to update that design, incorporating any new advances in robotic technology.

Across the pond, the European Space Agency (ESA) is focusing on improving double-walled isolators — stainless-steel containment units with two chambers of different pressures — that would house samples during hands-on research. According to Allen, the ESA is testing new methods of sealing instrument entry points, one of the main places where leaks can occur.

The push for innovation isn't over yet. The Mars 2020 lander could likely collect core samples from the Red Planet, the first step in returning them to Earth. And that's a key motivator for space agencies, Allen says: "We have gone through cycles of Mars sample return being close, and each time that has spurred a new set of technology and design studies. Now, that's beginning to happen again." Readiness could be right around the corner. —BRENDA POPPY

DID YOU KNOW? Much like *Fight Club*, herding sheepdogs have two main rules: 1) Bring sheep together. 2) Drive them forward once they're collected. The finding may have applications for crowd control and for guiding groups of exploratory robots, researchers at Swansea University say. For the study, both sheepdogs and sheep wore GPS-fitted backpacks. (Or should we say, baaackpacks.)

FROM TOP: NASA/JPL-CALTECH; ESA-ANNEKE LE FLOC'H; NASA

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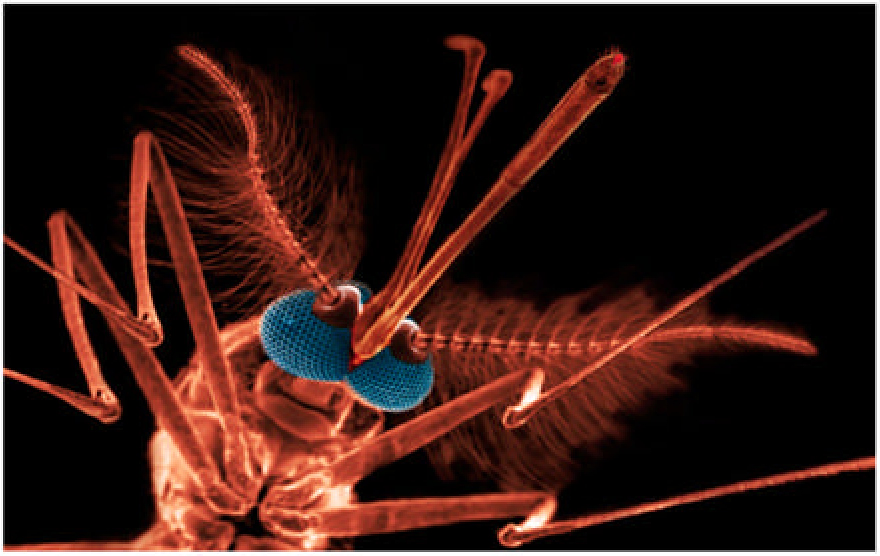
Mosquito, Modified

A remarkable scheme to alter the pest's DNA could change the disease-carrying species for the better — or wipe them off the Earth.

BY **JEFF WHEELWRIGHT**



The *Anopheles* mosquito, shown in an electron micrograph, spreads the malaria parasite.

Mosquitoes have pestered mankind for as long as we've had the wits to swat them. A mere annoyance in the temperate zones, mosquitoes in the tropics carry serious diseases, such as malaria and dengue fever. The former causes more than half a million deaths each year, mostly among children under 5, and the parasite responsible for malaria keeps growing more resistant to drugs. Meanwhile, the World Health Organization considers dengue fever the most important viral-borne disease in the world, with cases since World War II increasing thirtyfold — up to 50 million annual infections.

If you block the mosquitoes, the diseases' vectors, you block their microbial payloads, but that's easier said than done. Since DDT was taken off the market, mosquitoes in Africa, Asia and Latin America have evolved resistance to today's less toxic chemical sprays. Biological methods, which pit other organisms (ranging from fungi to fish) against mosquitoes, have seen only partial success.

Their options dwindling, researchers have turned to genetic engineering as the last resort and new frontier of mosquito control. The ambitious goal here is to alter the mosquito's DNA: to insert a change on the chromosomes of not just laboratory captives, but of an entire species.

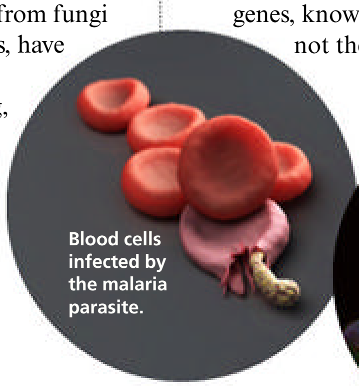
There are two basic approaches. The more radical of the two, known somewhat euphemistically as population suppression, would insert a biochemical self-destruct mechanism into the insects' DNA, a time bomb to wipe out the whole species. Under the milder scenario, called population replacement, genetically modified mosquitoes would gradually displace the wild ones. For example, in experiments, scientists have transplanted genes to make the *Anopheles* mosquito resistant to the *Plasmodium* parasite that causes malaria.

For the dozens of labs at work on the problem, coming up with useful genes, known as transgenes, is not the hard part — it's how to transfer enough copies of the transgenes into free-ranging populations. But if the mosquito has an Achilles' heel, it is the mating instinct of the males, which fly like guided missiles to any females in the area.

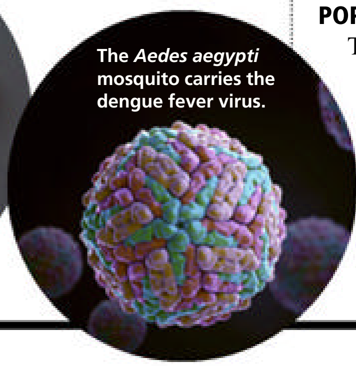
So the research strategy is to send males fitted with a DNA warhead to breed with females. Let go by the millions, the altered males outnumber and outbreed their wild counterparts, and a large fraction of the following generation of mosquitoes inherits the transgene. Ideally, the process fuels itself, as one generation passes the gene to another until all are infected. "Once modified mosquitoes are introduced," says Nikolai Windbichler, a biologist at Imperial College in London, "essentially the mosquitoes carry out the work for us."

POPULATION DECLINES

That's how it goes in theory. So far, only one biotech company, the British firm called Oxitec, has conducted trials of modified mosquitoes in the field. Oxitec's target is *Aedes aegypti*, originally an inconsequential mosquito species in the forests



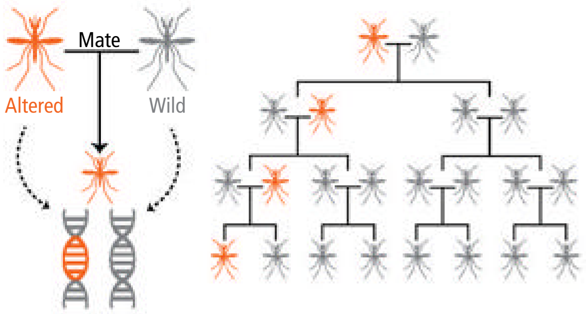
Blood cells infected by the malaria parasite.



The *Aedes aegypti* mosquito carries the dengue fever virus.

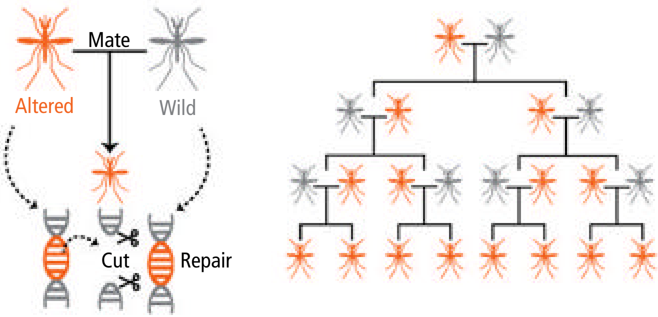
TOP: THIERRY BERROD/MONA LISA PRODUCTION/SCIENCE SOURCE. BOTTOM: SCIENCE PICTURE CO./SCIENCE SOURCE (2)

NON-GENE DRIVE



One copy of the altered gene is inherited, leading to a 50 percent chance of passing it on per generation.

GENE DRIVE



By altering both chromosomes, gene drives ensure both copies of the altered gene are inherited, leading to a 100 percent chance of passing it on.

ALISON MACKEY/DISCOVER AFTER P HUEY/SCIENCE, AUGUST 2014: VOL. 345 NO. 6197 PP. 626-628

of North Africa but now a worldwide carrier of dengue fever.

Manipulating male mosquitoes raised from eggs, Oxitec injects a gene that makes a lethal protein in the bugs' bodies. The transgenic males don't die because the gene is inactivated by tetracycline (a common antibiotic), which is part of their diet in the lab. Once released, the modified males round up most of the local females. The offspring of these matings express the lethal protein in their cells, and they die well before maturity because there's no tetracycline antidote in their environment.

Field trials of this method in the Cayman Islands (2009-10), Panama (2014) and Brazil (ongoing) showed good results, the company says. For several months, the process knocked back local populations of mosquitoes by 80 percent or more. The next Oxitec release may soon take place in the Florida Keys if U.S. environmental agencies approve. The area has seen a recent smattering of dengue fever.

A drawback of this method is that mosquitoes must be released repeatedly because the lethal genetic effect persists only for one generation. On the other hand, that can also serve as a brake if something goes wrong.

Windbichler's group at Imperial College has come up with a longer-lasting system called the X-shredder, referring to the mosquito's X chromosome. The subjects of the experiments are *Anopheles* mosquitoes, which transmit malaria.

All things being equal, natural selection will eventually scrub the gene from the population. However, all things are not equal in the world of biotechnology.

Again, the males are altered, this time with a transgene for an enzyme that cuts up DNA. In mosquitoes, as in humans, the sex-determining chromosomes are X and Y. When a male mosquito produces sperm, just one of these two chromosomes is copied. If a sperm cell contains an X, the X-shredder enzyme slices it up, in effect aborting the cell, while sperm cells containing the Y chromosome can proceed to fertilization. Because female mosquitoes always produce an egg with an X chromosome, the mosquitoes that survive are all XY — only males.

Windbichler's technology, if scaled up, could establish the X-shredder gene in half the males of a given population. As they mated with a shrinking supply of females, the X-shredder males would push the population lower until there are no female mates left. Windbichler says it will be some time before he can test the mosquitoes in the field, though. "We have to make sure that all aspects of safety and ethical considerations have been addressed," he says.

INSECT INFILTRATION

Scientists have learned that genetic tinkering exacts a cost on an organism, as if the weight of the inserted transgene drags it down. A modified mosquito is less fit than its natural counterpart. This can be overcome temporarily with raw numbers, but all things being equal, natural selection will eventually scrub the gene from the population. However, all things are not equal in the world of biotechnology.

A new tool, CRISPR-Cas9, is revolutionizing the field by allowing researchers to edit the genomes of just about any species, and to outfox natural selection in the process. The tool harnesses a DNA-cutting enzyme, Cas9, from the same family of enzymes as the X-shredder. Guided by specially tailored RNA molecules, the gene for the enzyme can be inserted anywhere on the chromosomes, and it delivers an attached transgene to the site, like a locomotive pulling a freight car.

Inserting a CRISPR-Cas9 complex — made up of the cutting gene, the RNA guide and the transgene — on a mosquito chromosome immediately

snips out a place on the complementary chromosome. (All chromosomes come in pairs.) Then the complex copies itself.

Thus, the mosquito gets a double dose, ensuring it will pass along the transgene since both chromosomes have been altered. And when it reproduces, not only does the offspring reliably receive a copy of the transgene, but that inherited copy immediately makes a copy of itself, too. So unlike Windbichler's shredder, which reaches only half the males in a mosquito population, CRISPR-Cas9 drives its transgene through the entire horde, thanks to internal duplication. Hence the term *gene drive* for this prospective new weapon in pest control.

Kevin Esvelt, a specialist in molecular evolution at Harvard, helped develop the principles of CRISPR-Cas gene drives. In 2014, he and his colleagues published warnings to biologists to be careful with the technology. "It's not the sort of thing that should be worked on in obscurity," he says. "The public has the right to know what we are attempting to do with this technology." Esvelt believes that immunizing mosquitoes against the malaria parasite, a positive application of CRISPR-Cas9, is a better place to start than eradicating a species with a lethal gene drive.

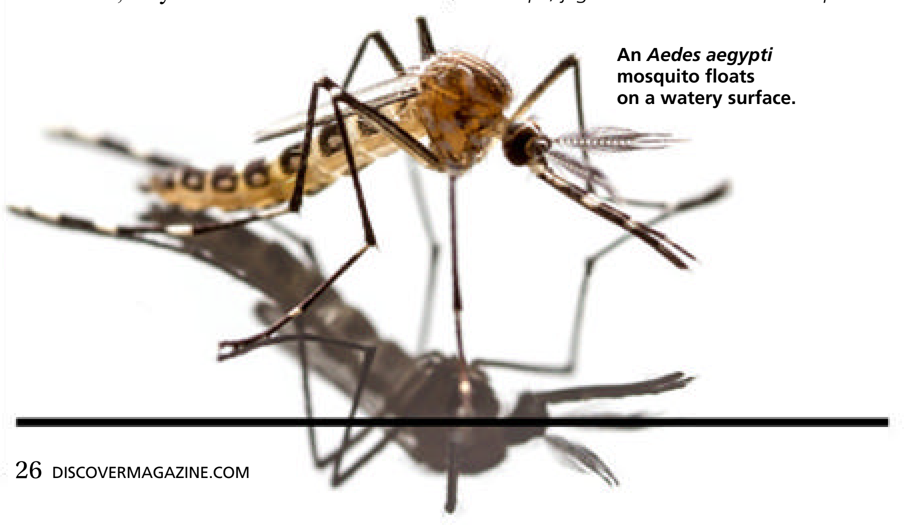
Whatever the plan, the public must give consent. "People are honestly concerned about altering wild populations, and that's because they are part of the shared environmental commons," says Esvelt. "You need to look at, 'Do they still pollinate the flowers that they're supposed to pollinate?' You need to run all these things by the ecologists and make sure it doesn't look like it's going to do anything bad."

Simon Warner, Oxitec's chief scientist, compares a gene drive to a genie in a bottle. "Once it's out of the bottle, it's gone," he says. But even then, Esvelt argues, a solution exists: just launch a second gene drive. "We can build another drive to reverse the genomic effects of an earlier one. If a gene drive causes a problem, then we can release a reversal drive that targets the genomic changes made by the first drive and undoes them. And that is a key, key safety measure."

It's a good bet that releasing one gene to neutralize another would not be a wildly popular plan. By contrast, "Oxitec's technology is self-limiting," says Warner. "The modified mosquitoes don't survive — they don't persist in the environment. They go away pretty fast."

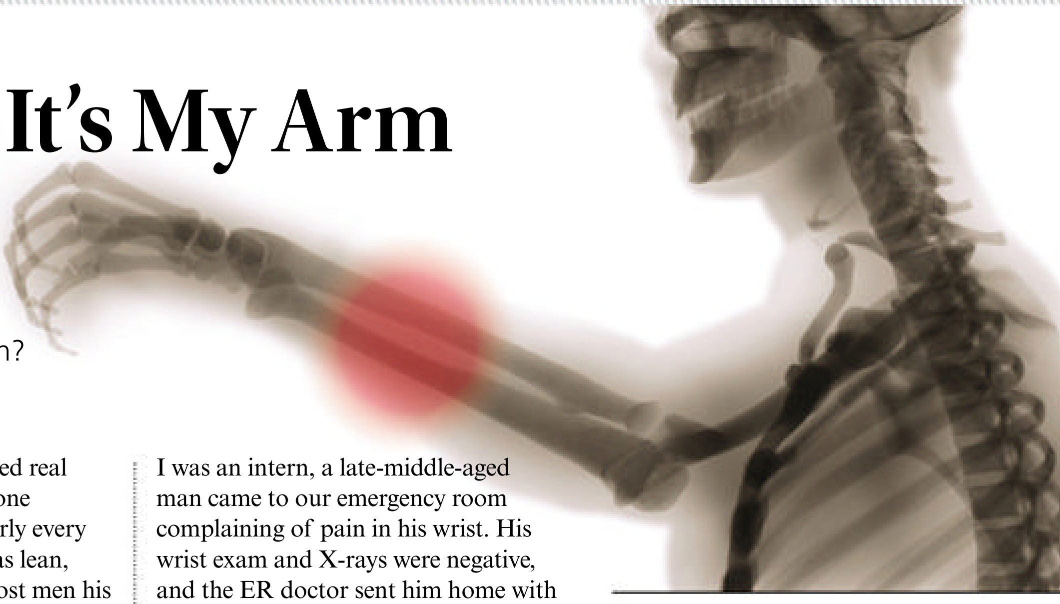
Having gained the approval of regulators in several countries, Oxitec's technology is out in front of the other approaches. Its strategy seeks to suppress mosquito populations selectively, in and around urban areas, and so reduce disease where people live. If that doesn't work — watch out, mosquitoes. Lethal gene drives are revving their engines. D

*Wildlife lover **Jeff Wheelwright** has written for* Discover *on wolverines, pronghorn antelope, jaguars and invasive Asian carp.*



An *Aedes aegypti* mosquito floats on a watery surface.

ALEX WILD/ALEXANDERWILD.COM



Doctor, It's My Arm

Exercise-induced pain stops a healthy baby boomer in his tracks. Is his heart telling him to slow down?

BY **H. LEE KAGAN**

Phil, a 68-year-old retired real estate developer, had done high-altitude trekking on nearly every continent in the world. He was lean, athletic and healthier than most men his age. So when he called to tell me he was having arm pain when he exercised, it caught me by surprise.

"It happens whenever I do spinning. I start out OK, but maybe halfway through the class, my right arm begins to ache. It doesn't stop aching until I get off the bike at the end of the class."

He told me it had been going on for perhaps two weeks. He otherwise felt well. "Do you think it could be my heart?" he asked.

Ten years earlier, Phil had an episode of atrial fibrillation, a disturbance of his heart rhythm, triggered by a viral infection of the sac surrounding his heart. The infection, called pericarditis, along with the abnormal heart rhythm, resolved completely, leaving Phil with what we thought was a normal heart. Tests to check his coronary arteries were normal at that time.

Still, when I hear Phil or anyone complain about exercise-induced chest or arm pain, my first thought is angina, the pain produced by a heart not receiving enough oxygen-bearing blood flow because of a narrowed coronary artery. Physical exertion typically brings on the pain. Could a lean, fit trekker who had normal coronaries a decade earlier be having angina now?

CONTEXT MATTERS

The arm pain reminded me that when I was an intern, a late-middle-aged man came to our emergency room complaining of pain in his wrist. His wrist exam and X-rays were negative, and the ER doctor sent him home with some anti-inflammatory medicine. He returned the next night with the same complaint, was again seen and discharged. The next evening he came back for the third straight day, again with wrist pain. We called his private attending physician, Joe Pecora, and he told us to admit the man. That evening, we transferred him to the coronary care unit when chest pain began to accompany his wrist pain. An angiogram confirmed extensive blockages in his arteries, and he underwent coronary bypass surgery the next day.

"I don't get it," I later told Pecora. "How did you know the guy needed to be in the hospital?"

"I've known him for years," he said. "He owns a farm 40 miles outside of town. He's a hard-working non-complainer, up before dawn every morning taking care of business. If he takes time off three days in a row to drive 40 miles into town to be seen by a doctor, something is seriously wrong, and we'd better figure out what it is."

I never forgot Pecora's lesson about the importance of context when evaluating a patient and the value of a long-term relationship with a physician who knows you well.

"Come on over to the office," I told my patient with the spinning-induced arm pain. "Sounds like something that ought to be checked out."

But in my office, Phil's vital signs, physical exam and EKG were all normal. His heart sounded normal. His arm looked fine. I needed to flesh out the story a bit.

"When you're hiking or doing other kinds of exercise, do you get the same pain?" I asked. I was fishing for other activities that produce an increased demand for oxygen from a rapidly contracting heart. Like a clogged fuel line in a racing engine, if there is a blocked artery, a part of the myocardium, or heart muscle, becomes starved for oxygen when it beats quickly. This triggers a pain signal that travels along sensory nerves from the heart via the spinal cord to the brain. As it happens, the nerves bringing signals from the heart enter the spinal cord at about the same level as those from the arms. As a result, the mind's eye can perceive cardiac pain as arising in the arm, especially the left arm, though it can occur on either side.

"Actually," Phil answered, "it's just with spinning. When we hike up in the hills, it doesn't bother me."

"What about on the treadmill? Do you push yourself pretty hard?"

He nodded. "I'll go 45 minutes and get my heart rate up over 130," he said. "But that doesn't bring on

GUSTOIMAGES/SCIENCE SOURCE

the arm pain."

I became curious. If revving up his heart rate alone wasn't sufficient to trigger his pain, what was unique about spinning that made his arm hurt?

I had an idea. "Show me how you sit on the bike when you're in your spinning class," I said.

Phil sat on the end of my exam table, leaned far forward and mimed resting his forearms on the projecting handlebars of a stationary spinning bike. He held his head up so that he could still see forward.

"Is that how you hold your head when you ride?"

"Yeah. I like to be able to watch the instructor while I'm pedaling," he said.

"Show me exactly where you feel the pain when it occurs," I told him.

He held out his right arm, palm up. "It's mostly here," he said, indicating the lateral thumb side along the length of his forearm.

"Does it go into your hand as well?"

"Mostly the thumb."

"What about the rest of the hand and the other fingers? Do they hurt, too?"

He opened and closed his hand a couple of times. "Not really. Just the arm, thumb and maybe the pointer finger a little bit."

TOUCHING A NERVE

In my mind, I could see the anatomy and watched as the source of Phil's arm pain migrated north from his chest into his neck. He had outlined the sensory distribution of the sixth cervical nerve. (The spinal nerves are all numbered and identified as cervical, thoracic or lumbar — neck, upper back or lower back, respectively.)

Phil sat up, and I opened the Essential Anatomy app on my iPad. Its eye-popping, detailed graphics of human anatomy are always a hit when I use them to show patients what's gone wrong. I zeroed in on the skeleton at the neck. "There's a series of spinal nerves that come off either side of the spinal cord, starting at your neck and going

If revving up his heart rate alone wasn't sufficient to trigger his pain, what was unique about spinning that made his arm hurt?

almost all the way down to your rump," I explained. "Each nerve transmits sensations, including pain, from a specific, very circumscribed part of the body."

I pointed to the opening between the vertebrae, the stacked building blocks of the spine, through which the sixth cervical nerve emerges. "If this opening is narrowed by an arthritic spur or a flattened, protruding disc, the nerve can get pinched. Hyperextending your neck by raising your chin way up further narrows the opening and worsens the pinching. The nerve doesn't like that, and it generates a signal that is perceived as numbness, tingling or, as in your case, pain. The location of your pain maps out to an exact fit for the area served by the sixth cervical nerve."

I went on to explain to Phil that the absence of pain with other forms of exercise, the unique distribution of the pain and the association with extending his neck all argued against this being exercise-induced angina.

"I don't think it's your heart," I told him. "But let's see."

As Phil sat on the exam table, I had him raise his chin and tilt his head back and to the right. I put a little downward pressure on the top of his head with my hand as he did this. This posture maximizes the narrowing of the nerve-root opening, known as a foramen. In less than 20 seconds, I heard Phil say, "Ow. Yeah, there it is."

"The pain?" I asked.

"Yeah, in my arm."

I released his head. He brought his face forward.

"How about now? Is it going away?"

After rubbing his forearm for a few seconds, he said, "Yeah. It's nearly gone."

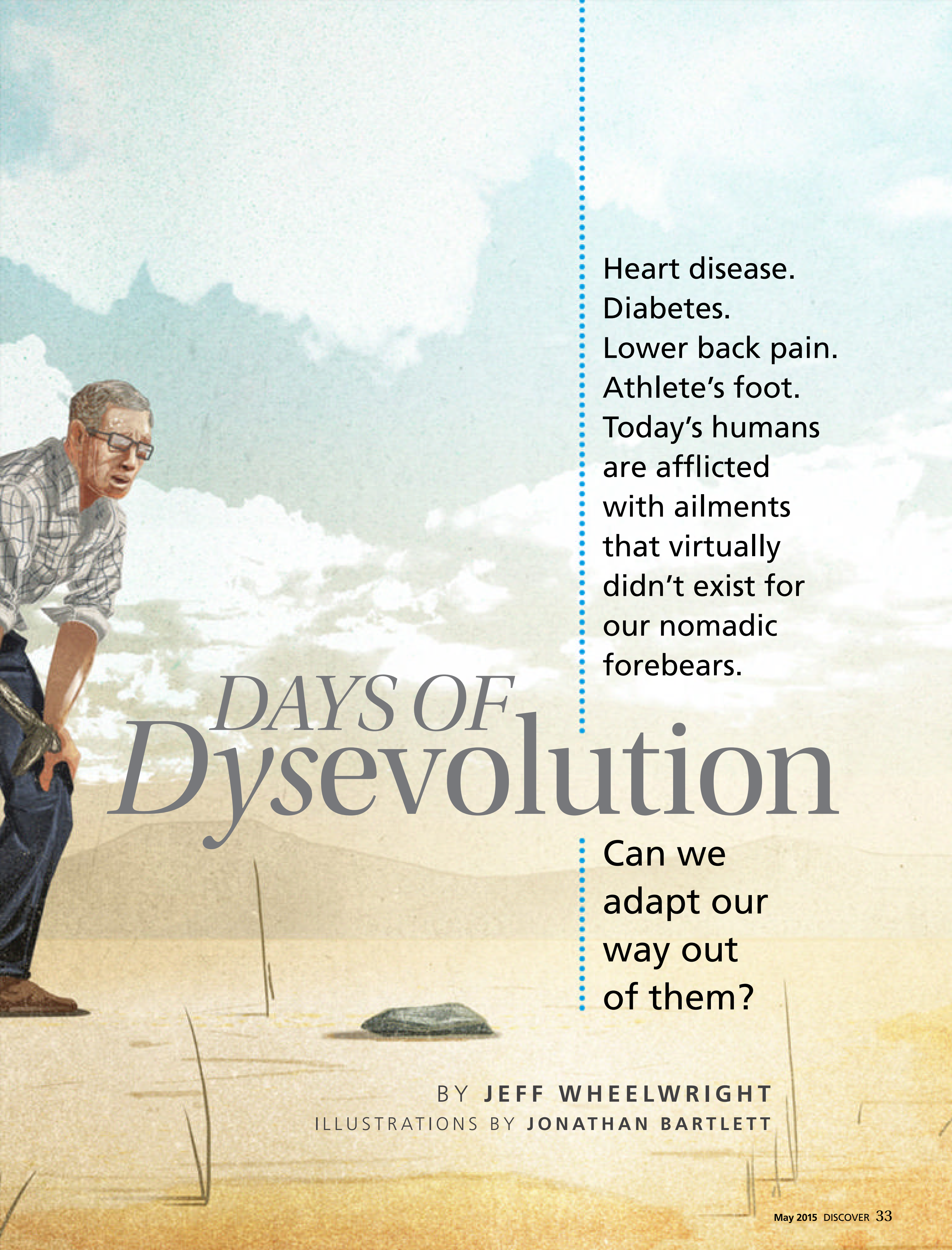
I was 99 percent certain that I found the source of Phil's pain. But I knew that he and his wife were planning to go trekking in Bhutan the following spring. Better to be 100 percent sure. In addition to X-rays of his cervical spine, I scheduled him for a cardiac stress test. He passed the latter with flying colors. The X-rays showed narrowed disc spaces at several levels in his neck.

I shared the results with Phil and told him that he didn't need a coronary angiogram. "What you need is to adjust your bike at the spinning studio. Drop the seat and raise the handlebar. That way, you're sitting more upright. You'll still be able to follow the instructor without craning your neck and pinching a nerve."

Phil's case reminded me of another bit of clinical wisdom I picked up along the way: Not every arm or wrist pain is angina. Sometimes a cigar is just a cigar. D

H. Lee Kagan *is an associate clinical professor of medicine at the Keck School of Medicine of USC. The cases in Vital Signs are real, but names and certain details have been changed.*

NICK VEASEY/GETTY IMAGES



Heart disease.
Diabetes.
Lower back pain.
Athlete's foot.
Today's humans are afflicted with ailments that virtually didn't exist for our nomadic forebears.

DAYS OF Dysevolution

Can we adapt our way out of them?

BY **JEFF WHEELWRIGHT**

ILLUSTRATIONS BY **JONATHAN BARTLETT**

I sat in my padded desk chair, hunched over, alternately entering notes on my computer and reading a book called *The Story of the Human Body*. It was the sort of book guaranteed to make me increasingly, uncomfortably aware of my own body. I squirmed to relieve an ache in my lower back. When I glanced out the window, the garden looked fuzzy. Where were my glasses? My toes felt hot and itchy: My athlete's foot was flaring up again.

I returned to the book. "This chapter focuses on just three behaviors … that you are probably doing right now: wearing shoes, reading, and sitting." OK, I was. What could be more normal?

According to the author, a human evolutionary biologist at Harvard named Daniel Lieberman, shoes, books and padded chairs are not normal at all. My body had good reason to complain because it wasn't designed for these accessories. Too much sitting caused back pain. Too much focusing on books and computer screens at a young age fostered myopia. Enclosed, cushioned shoes could lead to foot problems, including bunions, fungus between the toes and plantar fasciitis, an inflammation of the tissue below weakened arches.

Those are small potatoes compared with obesity, Type 2 diabetes, osteoporosis, heart disease and many cancers also on the rise in the developed and developing parts of the world. These serious disorders share several characteristics: They're chronic, noninfectious, aggravated by aging and strongly influenced by affluence and culture. Modern medicine has come up with treatments for them, but not solutions; the deaths and disabilities continue to climb.

An evolutionary perspective is critical to understanding the body's pitfalls in a time of plenty, Lieberman suggests. His argument is not difficult, and he is not the first to advance it. It's called the mismatch hypothesis: Our earliest, apelike ancestors foraged and hunted in small, mobile bands. For a million and more years in Africa, evolution adapted their bodies and behaviors in a give-and-take with a slowly changing set of environmental conditions — that's natural selection. Randomly trying out new features, keeping what works (an adaptation) and rejecting what doesn't, natural selection boosts an individual's fitness and survival over another's, to the benefit of the individual's offspring.

However, the invention of agriculture about 10,000 years ago disrupted the tortoise-like pace of adaptation. Life in settlements rapidly exposed human beings to novel foods, diseases and customs.


Harvard evolutionary biologist Daniel Lieberman.

JIM HARRISON

Hence the mismatch and, Lieberman contends, diseases that arise out of the transition from hunting and gathering to farming.

The Industrial Revolution, starting 250 years ago, accelerated cultural changes and left our bodies more out of sync with our environment. Consequently, our health suffered. Lieberman lists obesity, Type 2 diabetes, coronary heart disease, osteoporosis, hypertension and certain reproductive cancers as hypothesized noninfectious mismatch disorders, and likewise asthma, allergies, chronic insomnia, cavities, anxiety and depression, fallen arches, myopia and back pain. He later warns me "a majority of readers of the book are likely to suffer from and die from a mismatch disease." He also counts broad-scale infectious diseases as mismatches, though they've been mostly tamed in developed nations.

DYSEVOLUTION'S LOOP

Natural selection lacks the time to correct mismatches because cultural evolution moves so much faster today than biological evolution. Therefore, Lieberman proposes an ominous new term: *dysevolution*. It doesn't mean that human beings are going backward or that all our hard-won adaptations, like big brains and springy legs, have lost their value. Dysevolution is what Lieberman calls "the deleterious feedback loop that occurs over multiple generations when we don't treat the causes of a mismatch disease but instead pass on whatever environmental factors cause the disease, keeping the disease prevalent and sometimes making it worse." Health deteriorates when cultural evolution becomes the driver and certain adaptations, like an ingrained taste for sweets, become mismatches. Although he is appreciative of modern drugs and surgeries, Lieberman considers them "Band-Aids," equivalent to eyeglasses or arch supports, because they don't address ultimate causes or the possibility of prevention. "Once we get sick, treatment is part of the dynamic of dysevolution," he says.

Of the figures shown in these pages, the first three are products of Darwinian evolution, and the rest illustrate Lieberman's dysevolution. If we arrange the figures in a circle — a hominins' Wheel of Fortune — the one occupying the most favored position would not be *Homo sapiens* the post-industrial desk jockey, flush with material advantages (that is, someone like me), but *H. sapiens* the hunter-gatherer.

These first members of our *H. sapiens* clan evolved in Africa some 200,000 to 300,000 years ago from more primitive Paleolithic foragers. Their anatomies were like ours. Researchers know a fair amount about them from archaeological and skeletal remains and also from examining bands of more recent hunter-gatherers. These people were in great shape; they ran like marathoners and napped like lords. They had a nutritious, if chewy, diet. And if they

were not in perfect harmony with their environment, they were well adapted to it.

It's not true that hunter-gatherers died young, before heart disease and the like could manifest themselves. Those who survived infancy could live to around 70. Granted they had infections and parasites, but even at old age, they apparently didn't suffer from the chronic health conditions of affluent societies. Our Paleolithic cousins affirm the case, by counterexample, for the mismatch hypothesis, raising an obvious question: How might we become more like them? Using myself as a guinea pig, I submitted to Lieberman's analysis to find out.

BACK TO BASICS

In a course he teaches at Harvard, Lieberman collects exercise and dietary information from his students. The students compare themselves to tribal groups in Botswana, Tanzania and Paraguay who approximate the traditional hunter-gatherers. Sending him the same records and also my health information, I asked Lieberman where I fell on the spectrum between an average hunter-gatherer and the worst case. Also, how strong was the evidence that my health conditions, including serious illnesses I didn't have but was at risk for, were caused by evolutionary mismatches?

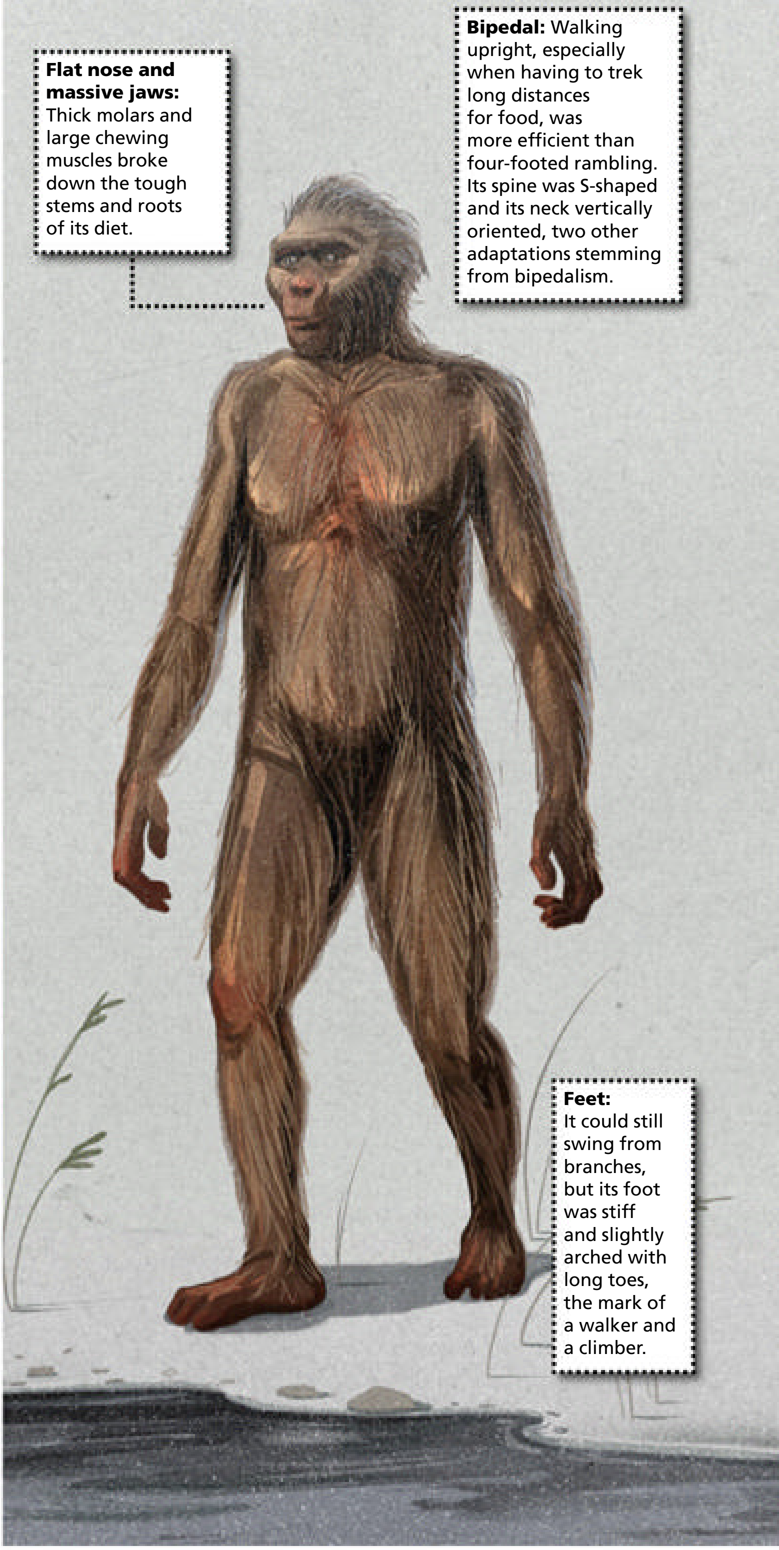
First, the basics. At 6-foot-2 and 198 pounds with a body mass index (BMI) of 25.4, I was at the "edge of overweight," Lieberman says. Although not obese, I was certainly heftier than a hunter-gatherer. One modern review of hunter-gatherer groups put their average BMI at 21.5, which health professionals consider low-normal. The lowest BMI provided by Lieberman, for female Bushmen (San people) in Botswana, was 18.2.

My systolic blood pressure (the pressure on arterial walls when the heart pumps), was 138, "a little on the high side," he says, qualifying me for pre-hypertension in some diagnostic circles. In Bushmen and other foragers, systolic blood pressure ranges from 100 to 122, which is below normal in developed societies. At 67, I may merit a pass for my blood pressure since it usually trends upward with age, yet hunter-gathers my age aren't ever hypertensive (systolic 140 or greater). According to field surveys, they don't have atherosclerosis (hardening of the arteries), angina, electrocardiogram abnormalities or heart attacks, either.

"It's also said they don't get diabetes," Lieberman adds, "but we don't know. I say it's extremely unlikely." Insulin resistance, a harbinger of diabetes, seems "rare and nonexistent in foragers," according to a 2007 paper by Boyd Eaton, Loren Cordain and Anthony Sebastian, experts on hunter-gatherer lifestyles. But, plucked from its formative environment, the hunter-gatherer is not immune to diabetes. Aborigines in Australia frequently become overweight and diabetic after they settle in urban

Australopithecus afarensis

About 4 million years ago in Africa, a four-legged, chimpanzeelike hominin with a small brain atop a wide face stood on its hind legs and walked.



Homo erectus

This early member of our genus evolved 1.9 million years ago and lasted at least 1 million years. Snoutless, chinless, long-armed and long-legged, *H. erectus* had the body plan of contemporary humans.

areas. In the late '70s, researcher Kerin O'Dea moved a study sample of Aborigines back to the bush for several weeks. Subsisting on lean kangaroo meat, fish and wild yams like their forbears, the Aborigines not only lost weight by foraging but also dramatically reduced their glucose levels and other metabolic signs of diabetes. Some were cured of the disease, at least temporarily.

Since there is no obesity, diabetes or heart disease in my corner, at least not yet, we turned to my less serious disorders that might be due to mismatches. Myopia? Nearsightedness is estimated to occur in just 3 percent of hunter-gatherers. "We know that in farming populations, it's almost nonexistent, too," Lieberman says. "I'd bet on that strongly as a mismatch." If children are using their eyes in different ways today, we should get them outside more, he advises. What's more, he suspects that eyeglasses are helping to keep genes for myopia prevalent in the human population. If so, that's an example of dysevolution.

My lower back pain stems not just from my forebears who stood up and became bipeds. Back pain is a tricky condition, Lieberman notes, because the mismatch may entail both underuse and overuse. Hunter-gatherers may suffer from back pain (it hasn't been assessed), but "we think they use their backs moderately," he says. They don't strain their backs like the farmers and factory workers who succeeded them, but they don't sleep on soft mattresses and sit around in comfy chairs as we moderns do, either.

How about anxiety and depression? "There's no data in hunter-gatherers," Lieberman says. "So why do we hypothesize it's a mismatch? Because stress levels are up. Less activity and sleep and modern diets all have proven effects on mood. I'll bet a fortune that chronic insomnia is a mismatch disease, too, but no one has ever studied insomnia among hunter-gatherers."

EVOLVED FOR ACTION

Lieberman has some personal insight on the benefits of physical activity, which he says has been helpful with his own anxiety levels. Running, in particular, is Lieberman's strong suit — a hobby that blossomed into a research specialty. At age 49, he runs or jogs 30 to 50 miles a week and walks about 2 miles per day. In fine weather he sometimes runs barefoot, earning himself a certain notoriety in Cambridge. Barefoot running is not for everyone, he says, but he justifies it in his book: "I have almost never seen a flat arch in any habitually barefoot person, reinforcing my belief that flat feet are an evolutionary mismatch."

Lieberman sees hunter-gatherers as professional athletes who never take a day off. Running barefoot after game and foraging for roots in the sub-Saharan heat, they would cover 5 to 10 miles every day. What happens to their descendants who

don't do that? A lack of regular vigorous physical activity "is one of the most fundamental causes of so many mismatch diseases, it's hard to know where to start," Lieberman says. Inactivity when young leads to "inadequate muscle, heart, bone and circulatory development" and when older leads to high blood pressure, cardiovascular disease and osteoporosis, which is rare in female hunter-gatherers. In archaeological deposits, the bones of the female forager don't show osteoporosis-related fractures. A woman's skeletal strength was forged by pounding, weight-bearing activity as she grew. Lieberman contrasts her with "today's sedentary post-menopausal woman who didn't exercise enough when she was younger." Dysevolution rears its head again: "By not having more physical activity in schools, we're actually condemning a large portion of our population to osteoporosis," Lieberman says.

Lieberman's aggressive workout regimen, along with his BMI of 21.5, might qualify him for the hunter-gatherer all-star team. But I likely would not make the cut. He had me wear a pedometer during my 2.6-mile morning jog, which is neither vigorous nor done every day. The walking or rowing I do on other days only moderately raises my heart rate. "In exceeding 150 minutes of moderate or vigorous exercise per week, you're in the top 20 percent of Americans," he says. "But you're at the low end of a typical hunter-gatherer. Maybe you're one-fourth hunter-gatherer."

Still, I am skilled at something that hunter-gatherers do: resting. Twentieth-century researchers often remarked that hunter-gatherers lie around a lot. Having no surpluses of food, they need to husband their calories. "Under such conditions," Lieberman tells me, "resting must be adaptive because it allows you to divert the remaining energy into reproduction and/or storage [fat to be used later]."

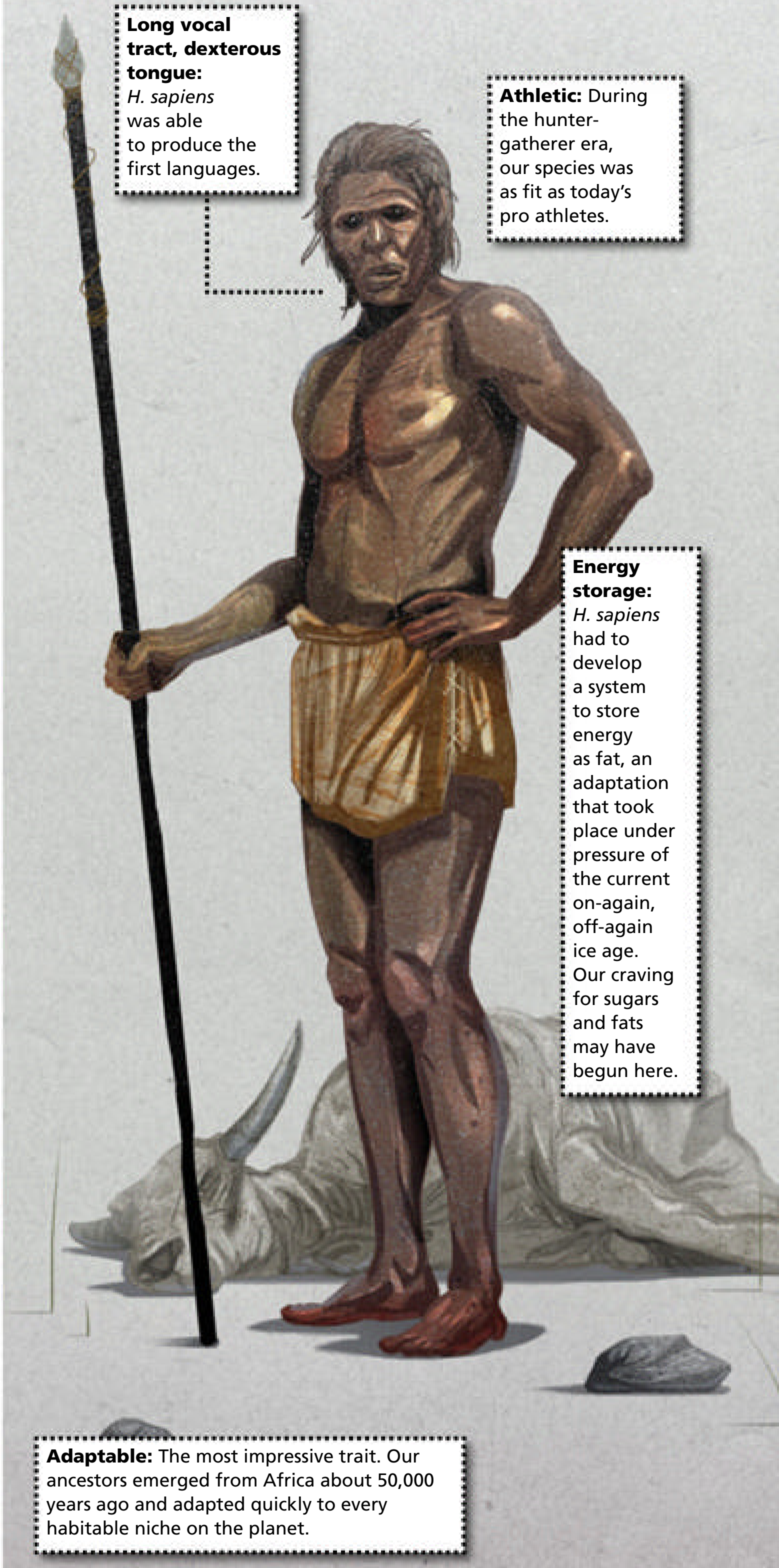
In lectures, Lieberman has speculated that people today aren't motivated to exercise because hunter-gatherers needed a lot of rest. To do nothing when you didn't have to was adaptive once, but it's maladaptive now. Thus, activity and inactivity were complementary traits, skillfully balanced by the hunter-gatherer but mismanaged by overweight moderns. The reasoning here seemed too easy. Although Lieberman has elucidated "tons of features" supporting our capacity to run and be active — among them springy Achilles tendons, muscular buttocks, big knees and myriad sweat glands — where was the scientific evidence for the evolution of human relaxation? "There's no good anatomical evidence for the adaptation for resting," Lieberman acknowledges. "It's supposition."

THE DYSEVOLUTION DIET

Finally, Lieberman appraised my diet. "I eat fewer cookies than you," he says at the outset. My meals

Homo sapiens (hunter-gatherer)

Our species arrived, scientists think, 200,000 to 300,000 years ago. Dark-skinned, narrow-hipped and fleet-footed. A rounder head had a face tucked below the brain.



Homo sapiens (farmer)

When the Paleolithic period gave way to the Neolithic, about 10,000 years ago, the only hominin on Earth was *Homo sapiens*. They settled down and began to raise crops and domesticate animals. This departure from the hunter-gatherer lifestyle led to most of the mismatch diseases from which we currently suffer, Lieberman says.

were a far cry from those of the average hunter-gatherer. The number of calories consumed was comparable, about 2,500 per day. But whereas my ancestor got most of his carbohydrates (starches and sugars) and about one-third of his calories from plants, nuts and seeds, my carbohydrates and the majority of my calories were derived from processed foods and dairy products, including cereal, bread, cheese, ice cream and, yes, cookies.

The tough wild plants and fruits of the Paleolithic foragers were high in fiber. I was dismayed to hear that my large helpings of salad and occasional grilled turnips contained only modest fiber, thanks to agricultural tinkering. “Veggies have been domesticated to have low fiber,” Lieberman says. “Your turnips are lower in fiber than wild tubers.” Although the hunter-gatherers ate much more meat and fish than I do, my dinner of, say, lamb shoulder chop contained more fat than their lean game.

Sugars, whether in the form of carbohydrates or the straight-up simple sugars, are Lieberman’s bête noire. “The word *addiction* should be applied to sugar,” he says. The hunter-gatherer was lucky to get a scoop of honey now and then, its sweetness a marker for an energy-rich food. Once the foragers learned about sweets, he or she must have wanted more. Indeed, the development of a taste for sweets, starches and fats, formerly a helpful trait, contributes to a number of mismatch disorders.

For example, my atavistic craving for Pepperidge Farm Double Chocolate Nantucket cookies no doubt is responsible for the 10 cavities I have in my mouth. “Cavities are an easy mismatch, a no-brainer,” Lieberman tells me, noting that in paleontological specimens, cavities are common in teeth only after humans began to cultivate grain and to milk cows — and nearly unknown in hunter-gatherers.

Largely because I keep my daily calories under control, “a nutritionist would say you eat a healthy diet,” says Lieberman, “and not an unreasonable amount of processed foods.” But from the perspectives of the true hunter-gatherer and his modern acolyte, the paleo dieter, “what pops out are the levels of dairy, the amount of sugar in ice cream, the cookies and pie. Looking at the dairy, processed foods and relative lack of fiber, the paleo-diet person would faint.”

For all that, a health and nutrition panel hired by *U.S. News & World Report* gave the paleo diet its lowest ranking. The diet was faulted for having too much animal protein and not enough carbs and calcium. Its good points are its fiber and potassium and the absence of salt. Lieberman is dismayed that beans and lentils are verboten. “Just because something is novel and was not eaten by our ancestors, that doesn’t mean it must be unhealthy,” he says. “That helps explain why I am content to eat legumes and moderate amounts of dairy even though

my Stone Age ancestors didn't eat peanut butter sandwiches washed down with a glass of milk."

CULTURAL COUNTERATTACK

Although human beings are still evolving, Lieberman doubts that natural selection can overtake our quicksilver culture and rectify our health problems. "I care about my children and grandchildren. I'm not going to wait for natural selection. It's not that rapid," he says. He favors fighting dysevolution on its own terms, by cultural means. Unhealthy habits and products will be passed down the generations as long as the advantages — convenience, low cost, appealing taste — are seen to exceed the disadvantages. What he calls cultural buffering, from protective clothing to antibiotics, screens the body from the harshness of the environment and of evolution. "Lack of selection, because of antibiotics, say, leads to an increase in [human] variation. People who might have been filtered out won't be. They'll pass on their genes," he says.

"I'm not opposed to cultural buffering, to taking care of the weak. But treating takes away time and energy from preventing. We don't hear about preventing cancer. For example, exercise can lower the risk of breast cancer by 20 or even 50 percent. Who does preventive ophthalmology? Preventive podiatry?" In short, if more doctors preached evolutionary medicine, patients might understand the big picture of why it's hard for them to lose weight or eat right, which might make them amenable to learning how and trying harder. To substitute a mismatch condition for a failure of will might do great things for motivation.

The hunter-gatherer is an important messenger in Lieberman's public health campaign, but his lifestyle isn't a panacea. "Arguably, people in the developed world are better off than hunter-gatherers ever were," he says. "We are living longer and healthier today. Infectious diseases have been conquered. Life wasn't necessarily better back then. We've just swapped challenges."

My own implicit challenge from Lieberman was to cut down on ice cream and cookies. But first I sought some cultural buffering by having my total cholesterol measured. At 184, it wasn't in the lowest range, but it wasn't too bad, agreed my doctor. My weight was holding steady, and I had no signs of hardening of the arteries. After further consultation with my inner hunter-gatherer, I decided that my lifestyle is fine as it is. D

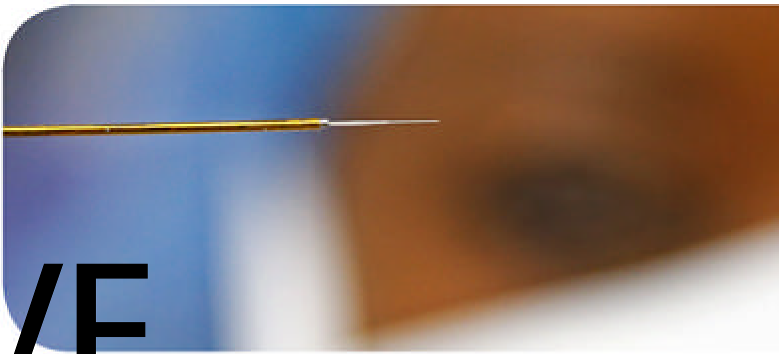
Contributing editor ***Jeff Wheelwright*** *is author of* The Wandering Gene and the Indian Princess: Race, Religion, and DNA.

How can we fight dysevolution? Read Lieberman's proposal at **DiscoverMagazine.com/Dysevolution**

Homo sapiens (industrial/post-industrial)

The past 250 years have seen more change in culture than the previous 250,000 years, dwarfing the changes to the human body. The world's population booms, straining the world's natural resources.

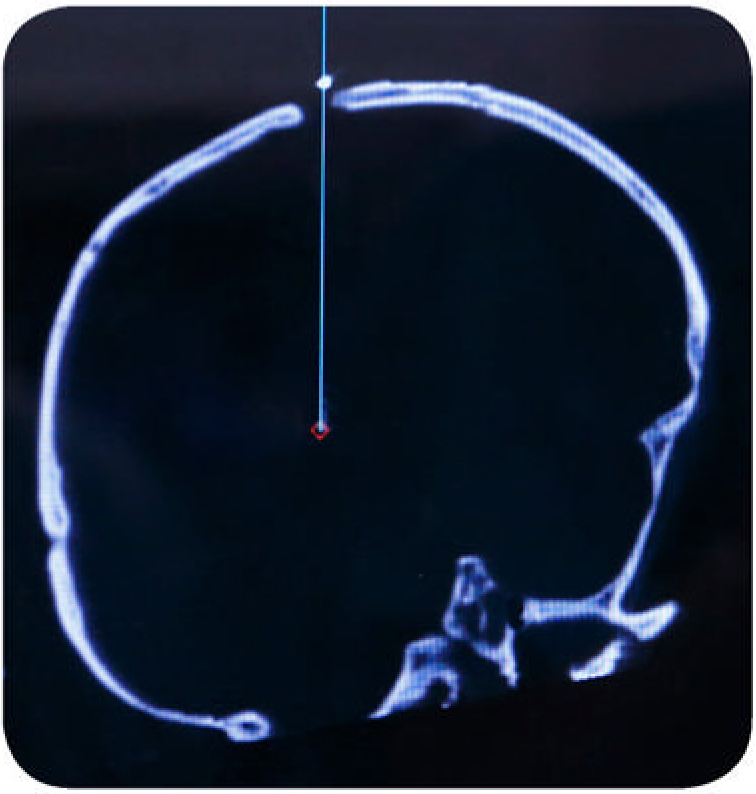
RESETTING THE



ADDICTIVE BRAIN

Researchers have begun to pinpoint the detailed circuitry that governs addiction. By rewiring those connections, they just might serve up a cure.

BY **ADAM PIORE**



Opposite: A surgeon uses an electrode to stimulate selected neurons in the brain of a woman with Parkinson's disease. Top: Deep brain stimulation involves inserting a temporary electrode the width of a human hair to find the best location and amplitude for a permanent electrode. Above: A scan shows the electrode descending through the skull to a spot where it will stimulate errant neurons. Researchers have found that remodeling the brain's connections can reverse addiction.

OPPOSITE: BERNADETT SZABO/REUTERS. THIS PAGE: BOB CROSLIN (2)

On a cold Tuesday morning one March, Christian Lüscher hopped on his bicycle in the cavernous basement tunnels that snake beneath the building housing his laboratory and pedaled to the nearby Geneva University Hospitals.

By the time he arrived in the operating room, a surgical team already had shaved a patient bald, secured a metal frame to her head and drilled two quarter-size holes on either side of her skull. She was 68, a retired U.N. employee.

Lüscher spotted her tremors immediately. From her fingers to her feet, the patient's whole right side shook four or five times a second as neurons deep in her brain fired spontaneously, sending electrical impulses toward her motor cortex and down her spine, and causing her muscles to contract involuntarily.

Lüscher, a neurologist who has spent years treating Parkinson's disease, was intimately

familiar with her condition. Yet, as the now 52-year-old scientist watched a neurosurgeon and his team prepare to use a technique called deep brain stimulation (DBS), a very different kind of patient was never far from his mind.

For nearly 15 years, Lüscher had spent his days focused on unraveling the mysteries of drug addiction. Now he believed he was tantalizingly close to achieving something that most would have thought impossible just a few years ago. By mastering DBS, Lüscher aimed to rewire the brains of drug addicts and actually reverse their addictions.

Standing near Lüscher in the OR, a neurosurgeon consulted a monitor displaying an image of the patient's brain. Then he slowly pushed an impossibly thin, electrode-tipped rod into her cerebral cortex, through the corpus callosum and beyond. A series of bliplike blasts began to fill the room. They were the amplified sounds of brain cells firing, picked up by the electrode and piped through a nearby speaker. Together, Lüscher and a fellow neurologist watched the Parkinson's patient closely, and listened. When the blips began to sync with her muscle twitches, they signaled the surgeon. They were close to the neural epicenter causing the uncontrollable tremors.

> What if treating addiction could be that simple? What would it mean to the millions of drug addicts and their loved ones? What would it mean for society?

The neurologist turned on a series of quick bursts of electrical current at the end of the electrode, adjusting its location and amplitude, until all the neurons in the target area began to fire. The twitching slowed. Then it stopped. He pulled out the temporary electrode and inserted a permanent one. The patient's ordeal was almost done. She would return in three days, and doctors would insert a battery-powered device in her chest, just below the collarbone. Then they would run extension wires up under the skin of her neck to the electrodes in her brain and turn it on. The tremors and paralysis would cease for as long as the device stimulated the errant neurons corrupted by her disease.

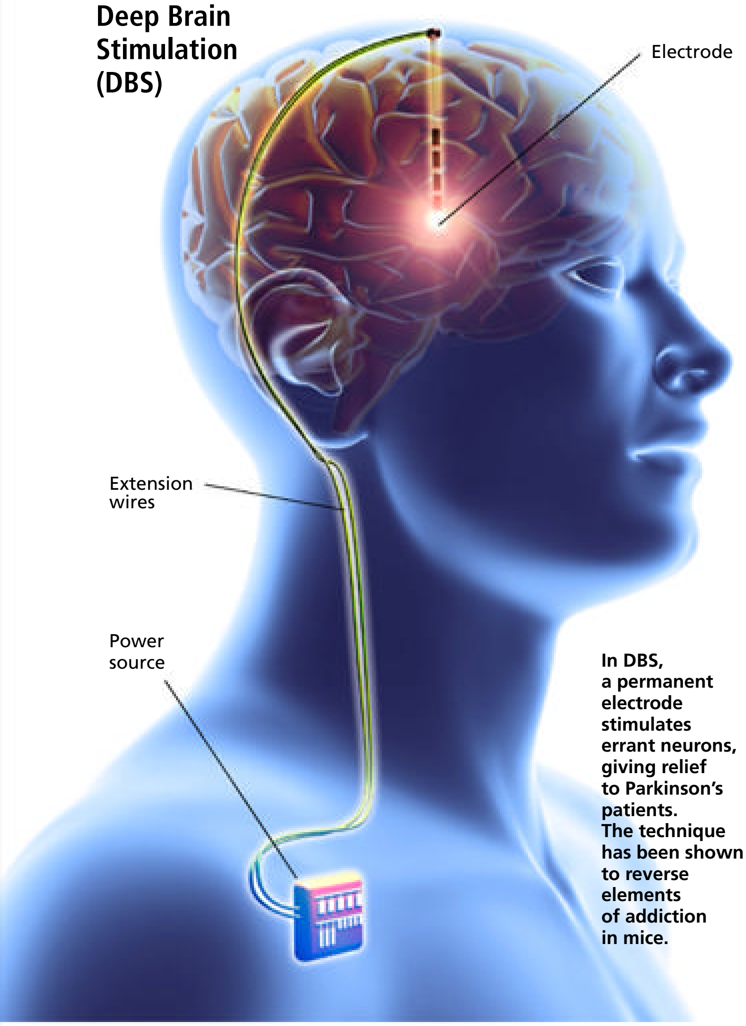
Lüscher bid farewell to the surgical team and rode back to his laboratory, buoyed by a tantalizing vision in the back of his mind. What if treating addiction could be that simple? What would it mean to the millions of drug addicts and their loved ones? What would it mean for society?

It's a vision that may be closer to reality than we think. In February, Lüscher reported in the journal *Science* that he succeeded in modifying the techniques used on Parkinson's patients to treat cocaine addiction in mice. Lüscher gave the mice a drug that temporarily blocked a key protein in the brain. Then he applied an electrical stimulus to a neural area that in humans is just a few centimeters away from the almond-shaped spot targeted in the Parkinson's patient, an area of the brain that scientists have come to associate with addiction.

Lüscher's results were unequivocal. The technique remodeled the mouse's brain and appeared to have reversed the key elements of addiction.

"It's a very pragmatic approach with a technique we hope to apply to humans in the future," Lüscher says.

Deep Brain Stimulation (DBS)



In DBS, a permanent electrode stimulates errant neurons, giving relief to Parkinson's patients. The technique has been shown to reverse elements of addiction in mice.

AN UPHILL BATTLE

For years, people told Lüscher that his efforts sounded quixotic, even impossible. In the 1990s, when he was a newly minted Ph.D. just entering the field, many doctors and scientists refused to acknowledge addiction was a disease.

They'd stand up in the audience after his lectures on the biochemical basis of drug addiction: physicians, social workers, psychiatrists, many of whom spent every day on the front lines of the fight against the ravages of crack cocaine, heroin and oxycodone. They'd shake their heads sadly, as if about to deliver a hard truth to a family at the clinic.

"Let's not medicalize addiction," they'd tell him. "You're studying something that isn't real. It's psychological. There are no organic correlates."

For generations, medical evidence proving that addiction was an actual physical brain disease had eluded scientists. Alzheimer's causes massive brain-cell death and shrinks the outer areas of the organ. Cancerous tumors stand out against the brain's Jell-O-like ridges, like craters on the moon. No such clues were visible in the brains of dead addicts — though they

PASIEKA/SCIENCE PHOTO LIBRARY/CORBIS

often left behind plenty of visible wreckage in their own lives.

"The gold standard to determine whether someone has a disease is to do an autopsy," Lüscher says. "But with the standard tools that pathologists have, there is not much wrong in the brain of an addict."

Lüscher knew better than most that it was a fallacy to suggest drug and alcohol dependency was largely mental, and thus a matter of will. As a postdoc in 1996, Lüscher traveled to the University of California, San Francisco, and participated in an experiment that helped unravel the mysterious biochemical changes connected to learning and memory.

Some forms of associative learning, Lüscher and his colleagues demonstrated, were reflected in the appearance of microscopic proteins called AMPA receptors. These receptors bloomed at the tiny cleft where two neurons meet, known as the synapse, and "wired" the neurons together with a stronger bond. Lüscher was convinced that these same processes would someday explain addiction.

So, in those early lectures, Lüscher would stand in front of the doubters, listen politely to their criticism, and then explain why they were wrong. Addiction didn't kill neurons; it somehow remodeled the connections between them in a devastating and maladaptive way. And someday soon, scientists would find a way to prove it.

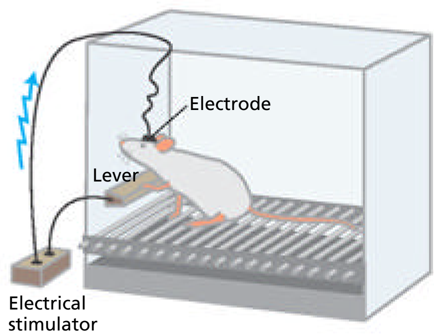
That day finally arrived in 2001, when a UCSF team electrified the field of addiction research by isolating distinct, long-lasting biochemical changes that appeared in the brains of mice after exposure to cocaine. This "addiction trace" was proof that addiction was a medical condition; the evidence of the mysterious mechanisms in play had been slowly building for years.

THE BRAIN'S SWEET SPOT

The discovery that sparked the age of modern addiction research occurred entirely by accident. At a McGill University lab in the early 1950s, postdoc James Olds was hunched over a rat, trying to attach electrodes to the area of its brain he suspected was associated with pain.

Olds and graduate student Peter Milner planned to zap the rat every time it wandered into a specific corner of the cage. But far from recoiling when the electrode was activated, the rat seemed to enjoy the experience. Instead of avoiding the corner, the rat hurried back to it. When the two men investigated further, it turned out that during setup, the electrode had jarred loose and lodged into another nearby area of the brain.

Olds and Milner modified the experiment, offering the rat a way to self-administer the pulse by pressing a lever. When they placed the electrode at a particular sweet spot, some rats pressed the lever hundreds of times an hour. In subsequent experiments conducted by Olds, some rats pressed the lever as many as thousands of times an hour. They ignored food and water. Some self-stimulated until they collapsed from exhaustion.



Rats will press a lever — hundreds of times an hour — to stimulate the brain's "pleasure center."

Neurologist Christian Lüscher has worked 15 years to try to crack the code of what happens in the addicted brain.

Olds hypothesized that the area consisted of interconnected circuits of brain cells that could be excited by the satisfaction of basic drives, circuits of the brain that perhaps contained the very seat of hedonism itself. A newspaper gave the area its famous name: the "pleasure center."

It wasn't much of a stretch to relate the behavior of these compulsively self-stimulating rats to that of human alcoholics or drug addicts on a binge.

In the 1970s, researchers began to home in on a specific neurochemical substance at work in the brain. Scientists already knew the brain's main signaling agents were neurotransmitters, chemical messengers released by a neuron when it's activated. These messengers travel across the synapses connecting the excited neuron to its neighbors and bind with proteins on the surfaces of the neighboring cells. This, in turn, affects how many positively charged ions are allowed into these neighboring cells' interiors, and how likely they are to fire electrical pulses of their own. When they do, they release neurotransmitters to their neighbors, which causes them to switch on, and so on.

Researchers thought these neurotransmitters were involved in the compulsive behavior of the drug-seeking mice. Roy Wise wanted to figure out which one. Whereas Olds stimulated rats' brains directly with electrodes, Wise, then a researcher at Concordia University in Montreal, did so indirectly with intravenous tubing used to deliver drugs like amphetamine. He hit the jackpot when he fed rats pimozide, a drug that blocks the neurotransmitter dopamine. On low doses, the rats tried pressing the lever faster to increase the dose of amphetamines. When Wise fed them large doses of pimozide, they lost interest. The implication seemed clear: Dopamine was needed for amphetamines to stimulate the pleasure center, and its presence somehow helped spur the compulsive behavior.

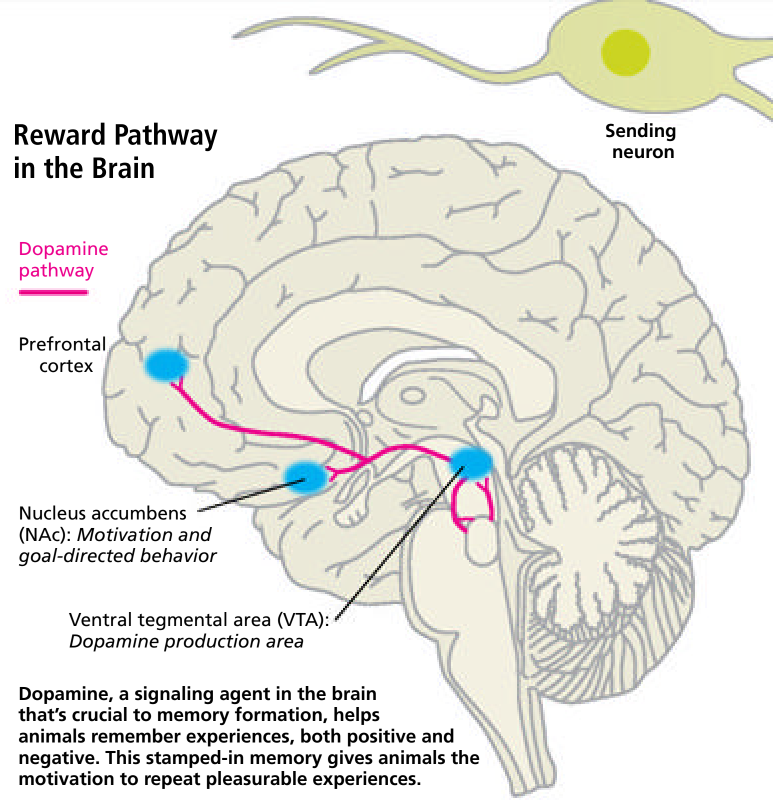
Researchers also demonstrated that if you produced lesions in the brain's supply center of dopamine, the rats lost

TOP: CHRISTIAN LÜSCHER. BOTTOM: ALISON MACKEY/DISCOVER

interest in amphetamines. The ventral tegmental area (VTA) and a related adjacent area called the nucleus accumbens (NAc) were crucial to the dopamine system. The effort to definitively prove and flesh out the theory — known as the dopamine hypothesis — became the linchpin of addiction research for the next 30 years.

By the mid-1990s, most addiction researchers came to believe that dopamine's role is more complex than a simple pleasure juice. Dopamine serves as a learning signal that helps animals remember pleasurable experiences and develops the motivation to repeat them. But this signal somehow goes awry with addiction. Research also has demonstrated that dopamine needed to be present for rats to remember unpleasant experiences, such as electric shocks. When an animal experiences any intense stimulus that is worth remembering, dopamine is released in the brain.

"One of the things that has been stressed in recent literature is that the dopamine system is activated by stress," says Wise, who is now at the National Institute of Drug Abuse (NIDA). "These [stressors] are not pleasant, and yet they stamp in memory as effectively as pleasurable experiences. Dopamine is responsible in both cases."



Dopamine, a signaling agent in the brain that's crucial to memory formation, helps animals remember experiences, both positive and negative. This stamped-in memory gives animals the motivation to repeat pleasurable experiences.

MEMORY AND RELAPSE

One of the most vexing aspects of addiction is relapse. It's not just that addiction overcomes resolve, even when a relapse threatens livelihoods, relationships and the addict's very life. It's that the compulsion to use lingers long after the drug of choice has left the addict's body. How do the demons of this invisible disease persist when no physical trace can be found?

To many, the answer isn't complicated: It's as simple as bad character, selfishness. But in recent years, addiction researchers have compiled mounting evidence showing that addiction is a maladaptive form of learning somehow etched permanently into the most primitive areas of the brain. The chemical tool that leaves that mark, researchers long suspected, is dopamine. Yet to prove it, they needed to find evidence of the mark itself.

When an animal experiences any intense stimulus that is worth remembering, dopamine is released in the brain.

To do that, first they would need to answer a more basic question: If addiction is a maladaptive form of learning and memory, how precisely do normal learning and memory work?

It was a question at the heart of research in the labs of two UCSF researchers, Rob Malenka and Roger Nicoll. Their work, in many ways, would set the stage for the revolution now overtaking the field of addiction research.

Malenka and Nicoll knew that our memories connect to one another through a vast matrix of associations, a principle poetically articulated by neuroscientist Carla Shatz: "Cells that fire together, wire together," she wrote. "Cells that fire out of sync, lose their link." Put another way, the coincidental firing of two neurons close to each other somehow causes the connections between them to strengthen. That strengthening at the synapses makes them more likely to fire together in the future.

In the 1990s, Malenka and Nicoll were at the center of the race to unravel the precise chemical processes underlying this phenomenon, known as long-term potentiation (LTP). The key to solving the mystery lay in understanding how signals are passed between neurons. A neuron fires only when the ratio of positively to negatively charged ions inside its membrane rises above a certain point. For that to happen, millions of tiny, electrically charged ions must get inside the cell through specialized gated proteins.

In the hippocampus and the amygdala, areas of the brain thought to be associated with episodic memory, researchers had shown that the chemical signaling agent called glutamate acts like a key in the lock of some of these protein "flood gates." Malenka and Nicoll focused on AMPA and NMDA, two different kinds of protein receptors on the surface of neurons that can bind with the neurotransmitter glutamate.

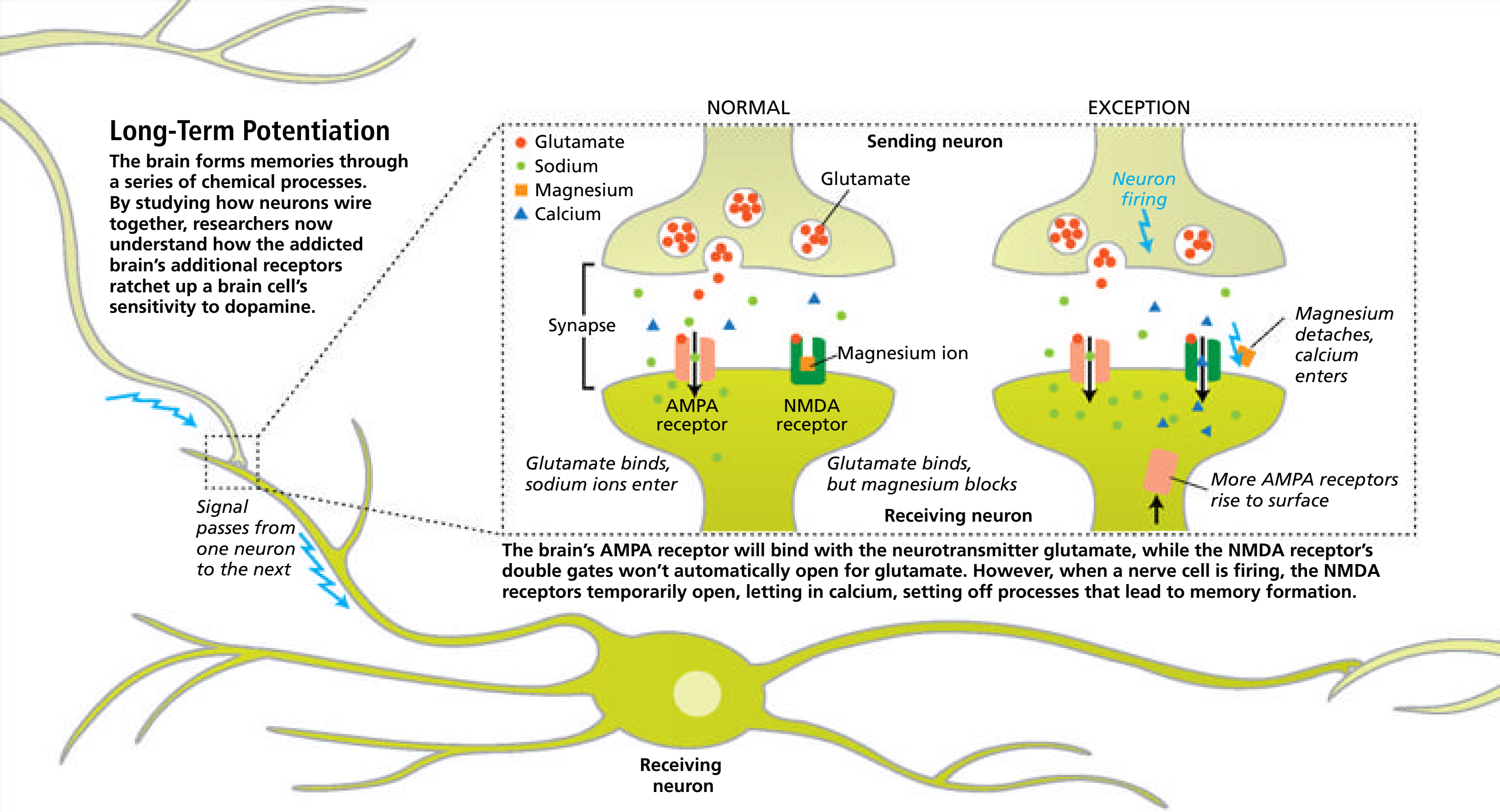
AMPA receptors will bind with glutamate any time it is released by a neighboring cell. The gates of AMPA receptors will open, and positively charged ions flood into the cell. But under normal circumstances, an NMDA receptor is like a locked door with a second door behind it. Even though glutamate can bind to NMDA receptors, it cannot open NMDA receptors' gates on its own because the gates are usually blocked by magnesium ions.

But there is an exception. If a neuron is already firing, its NMDA receptors undergo temporary changes. During spikes, the magnesium ions will detach at all synapses. The opening of this inner second door allows access to the interior of the cell.

The gates of the NMDA receptors are structured differently from those of AMPA receptors. And when NMDA gates open, calcium ions that cannot fit through AMPA receptors'

Long-Term Potentiation

The brain forms memories through a series of chemical processes. By studying how neurons wire together, researchers now understand how the addicted brain's additional receptors ratchet up a brain cell's sensitivity to dopamine.



The brain's AMPA receptor will bind with the neurotransmitter glutamate, while the NMDA receptor's double gates won't automatically open for glutamate. However, when a nerve cell is firing, the NMDA receptors temporarily open, letting in calcium, setting off processes that lead to memory formation.

openings suddenly flood the neuron's interior. The presence of calcium inside the cell, Malenka and Nicoll believed, acts like a cellular starting gun, setting off a complex cascade of chemical processes that results in LTP.

Malenka and Nicoll, along with their team, demonstrated that LTP occurs when calcium enters the cell and new AMPA receptors move to the cell surface. The presence of these additional receptors makes the cell more sensitive to future releases of glutamate from its neighbor.

What's more, by controlling the timing of an electrical stimulus, Malenka and UCSF researchers conclusively demonstrated that they could cause more AMPA receptors to appear on the outer membrane of a receiving neuron — or, conversely, to disappear.

Malenka then began to wonder if similar mechanisms might be at work with addiction, and he began a series of experiments that finally led to the smoking gun.

In 2001, UCSF researchers injected mice with cocaine, unleashing a flood of dopamine. Then they prepared mouse brain slices from a group of neurons in the dopamine production center, at 24 hours and every day thereafter. As they scrutinized the magnified slices of brain taken from their coked-up mice, Malenka and his colleagues collected the minute electrical recordings that documented the response of one neuron to the firing of its neighbor.

What they found exhilarated the nascent field of addiction research. The initial activity boost caused the neurons producing the dopamine to become twice as sensitive to additional stimulation from neighboring neurons for days, long after the cocaine had left the body. Only at 10 days did all trace of the changes dissipate.

Next, the researchers administered a drug that blocked NMDA receptors from responding to signals from neighboring cells when they introduced the cocaine, and no such sensitization occurred.

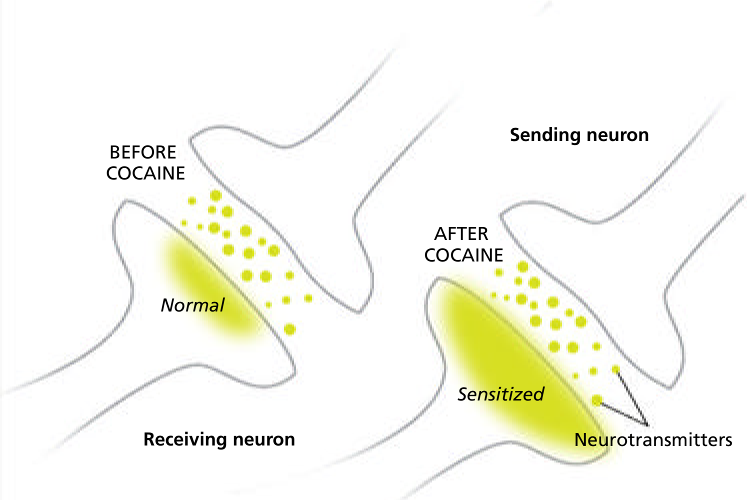
This was the first evidence that just one recreational dose of cocaine could hijack the mechanism that lay at the very basis of memory and learning — the strengthening of the connections between cells.

"This was the first step — it was the tip of the iceberg," recalls Malenka, now at the Stanford School of Medicine. "Addiction is a maladaptive form of memory and learning."

CLUE TO A CURE

Studies demonstrated that the changes in the brain's dopamine production area, or VTA — though crucial to the development of addiction — also triggered a cascade of biological processes that resulted in permanent changes in the nucleus accumbens (NAc), the area downstream that is closely linked to motivation and goal-directed behavior. These changes, in this crucial area of the brain, might help explain why addicts lose interest in natural rewards, some researchers suggest. (Addiction also causes changes in other areas of the brain, such as the cortex and the limbic system, that further influence these behaviors.)

In 2008, Marina Wolf, a leading addiction researcher who chairs the neuroscience department at the Chicago Medical School at Rosalind Franklin University of Medicine and Science, examined the key mystery of the field: the phenomenon of recurrent relapse, which strikes even those who have every intention of quitting their drug of choice. Wolf and her team trained rats to poke their noses in a hole to receive an intravenous dose of cocaine, which triggered a light cue. After 10 days of teaching each rat to associate the light with receiving cocaine, the team removed the cocaine tube, waited a day, and began measuring how hard the rat was willing to work to get the cocaine when the lights went on. The more times the rat poked the hole, the more motivated the rat



Researchers have found that in the brains of cocaine-addicted rats, their craving actually increased over time. Atypical receptors appeared on the surfaces of neurons and allowed calcium ions inside the cells. Their brains were then much more sensitive to drug-seeking cues.

was to get the cocaine and thus, the stronger its urge.

To those outside the field of addiction research, the timing of this motivation might seem counterintuitive. But researchers at NIDA demonstrated that there seemed to be an incubation period: The craving waned, but a dramatic spike in cravings followed. "In rats that have taken a lot of cocaine, craving becomes stronger rather than weaker as the withdrawal period gets longer," Wolf says. Similar research has shown that "if you go out a month and show rats the cue, the craving is much more. And it peaks at three months. Even six months down the line, the craving is stronger than at one day."

Indeed, by examining brain tissue and slices from the cocaine-addicted rats at various stages of withdrawal and craving, Wolf and her colleagues discovered that the incubation period and the subsequent spike in craving appeared to correlate with the appearance of atypical AMPA receptors on the surface of neurons in the NAc, which could help explain cocaine craving. These atypical AMPA receptors were missing a key subunit, called GluA2, that caused a change in shape and allowed calcium ions to enter the cell. As a result, when the animals see the cue and glutamate is released, the NAc neurons responded far more strongly to the cue, and the rats exhibited a far stronger craving. But the change also had other implications. Since calcium ions usually enter a cell through NMDA receptors only when a cell is already firing, the atypical AMPA receptors, by allowing calcium to enter the cell, disrupted the entire biochemical process of learning and memory in the primitive areas of the brain that are part of the very seat of motivation itself.

"Changing the way learning occurs in the nucleus accumbens is a pretty serious thing for the [future behavior] of the organism," Wolf says.

This period for sensitivity to relapse was counterintuitive, yet familiar to anyone who has watched a friend triumphantly quit cigarettes, alcohol or an addictive drug for a couple of weeks, only to relapse inexplicably just when it seemed they had beaten the bug.

"When we blocked these unusual AMPA receptors with a drug before testing the rats, we reduced their craving almost to normal levels," Wolf says.

SWITCH ON THE LASERS

Wolf's 2008 paper got Lüscher thinking. Might it be possible to somehow reverse the changes by artificially stimulating the NAc in a way that mimicked the way memories fade in the brain?

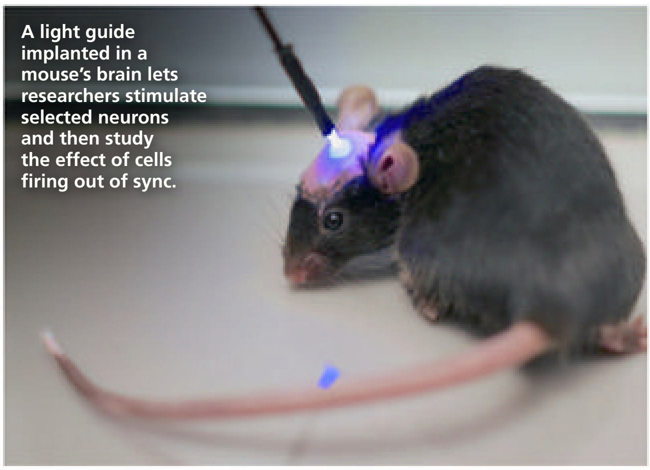
Lüscher proposed this seemingly farfetched idea to his 15-member lab team. He had just returned from a half-year sabbatical at Stanford University, where he mastered optogenetics. The technique genetically infuses individual brain cells with light-sensitive proteins (called rhodopsin) that would open up and cause the cells to fire — or cease doing so — in response to specific colors of focused light delivered through fibers.

By 2011, grad student Vincent Pascoli began his first experiments. Inspired by the idea that "neurons that fire apart, wire apart," Lüscher instructed Pascoli to attempt to artificially induce the chemical reactions known to weaken connections between two neurons. They aimed to prove that stimulating one synapse with an electrical pulse once a second for 10 minutes would weaken connections.

Previous experiments linked cocaine addiction with more drug seeking and increased sensitivity to the drug. One way to measure increased sensitivity was to inject a mouse with cocaine, place the mouse on a circular track, and count how many times it runs around the track. More sensitive mice are likely to run around the track twice as fast as a mouse receiving its first cocaine injection.

In preparation for his optogenetic experiment, Lüscher placed the mice on the track, timed their runs, fed them cocaine and put them back on the track. He then took slices of each mouse's brain and measured whether it led to an increase in the amount of electricity passing between neurons in the accumbens and the prefrontal cortex. The increase in electricity — and thus the presumed sensitivity of the mouse to cocaine — lined up perfectly with the rate at which the mice ran around the track.

When Lüscher and his team repeated the experiment, they followed up the cocaine with optogenetics. They drilled tiny holes in the mouse skulls and inserted light fibers through the brain tissue until they reached the NAc, where the neurons had been genetically modified to contain light-sensitive, gated proteins. Then Lüscher and his team shined a blue light



A light guide implanted in a mouse's brain lets researchers stimulate selected neurons and then study the effect of cells firing out of sync.

TOP: ALISON MACKEY/DISCOVER. BOTTOM: CHRISTIAN LÜSCHER

through light fibers, selectively stimulating some of the neurons. The stimulated neurons fired, releasing glutamate. But the low frequency of the firing and the amount of glutamate released wasn't enough to cause the neighboring neurons to fire.

University of Florida surgeons use mapping software to plan the insertion of an electrode into a patient's brain.

In other words, Lüscher's protocol created the conditions that caused the neurons to fire apart, which made them wire apart. Doing so, he hoped, would result in a disappearance of AMPA receptors from the surface, weakening the connections.

The results were clear. When they placed the mice back in the maze and gave them cocaine, they responded as if it was a first-time injection. The addiction sensitization had disappeared.

Lüscher's work, published in 2011 in *Nature*, implied for the first time that optogenetics could be used to reverse LTP, allowing researchers to manually erase learned behaviors. In a 2014 paper, Lüscher's team demonstrated that mice taught to self-administer cocaine over a longer time period also responded. Not only did this protocol lead to the removal of the defective AMPA receptors, but when AMPA receptors returned, they were normal again.

Lüscher is using DBS to remodel the connections between neurons because "cells that fire out of sync, lose their link."

Although there were still likely plenty of abnormalities present in his treated mice, Lüscher's 2011 optogenetics paper was among the first indicating we may be approaching a cure, or at least an age of powerful new interventions for addiction. In 2014, Wolf and her colleagues published work in rats suggesting that relapse in cocaine addicts also could be prevented by administering a non-toxic experimental compound that leads to the removal of the calcium-permeable AMPA receptors for about a day, thus reducing the ability of cocaine-related cues to trigger powerful craving that can lead to relapse.

"These compounds would not cure addiction. They would be something a recovering addict could take to maintain abstinence prior to entering a situation full of cues that might trigger relapse," Wolf says. "But right now, there are just no treatments for cocaine addicts, so even just a day of protection would be of great help."

Since optogenetics is considered far too invasive for humans, Wolf's technique had a clear advantage over Lüscher's. But Wolf's approach also had a downside: The injected drug traveled all over the brain, unlike Lüscher's localized optogenetic approach, which Lüscher believes also could lead to long-lasting changes.

Lüscher knows it will likely be many years before optogenetics is modified so it could be used in humans. Instead, he is focused on mastering DBS, which uses electrodes to stimulate groups of neurons rather than individual brain cells. Although some researchers have attempted to use DBS on addicts in various parts of the brain and say they have promising anecdotal results, no large-scale studies have been conducted, Lüscher says. And none of these experimenters has done so with the intent of reversing the synaptic changes brought on by the use of cocaine or other drugs of addiction.

Researchers still aren't sure precisely why DBS works in Parkinson's patients. The strong burst of electrical activity somehow immobilizes the neurons that cause tremors. And this is the same protocol that others have tried to apply to different parts of the brain to treat addiction.

Lüscher's approach is fundamentally different. He radically slows down the pace of the electrical stimulation of brain cells to match the rhythm of activations that he used to reverse addiction with optogenetics. Rather than tiring out neurons to temporarily immobilize them, as is done with Parkinson's, Lüscher is using DBS to remodel the connections between neurons because "cells that fire out of sync, lose their link."

DBS is far less precise than optogenetics, and the electrical field its electrodes create is larger and stimulates many more neurons than necessary. But Lüscher has discovered that if he administers a drug that temporarily blocks neurons from binding with dopamine, and then administers DBS, he is able to replicate his findings with optogenetics in mice.

"The two together still are not exactly the same as optogenetics, but it does the job," Lüscher says of DBS and the drug. "So it's a very pragmatic approach to try to translate and emulate what we have been successfully doing with optogenetics."

"It's a still long shot to go from optogenetics in mice to doing this on humans," Lüscher said as he sat in his lab one morning. "I am not sure if that will happen in my lifetime [as a scientist]. But DBS is an intermediate step. I am optimistic." D

***Adam Piore** is a* Discover *contributing editor.*

BOB CROSLIN

SANDS OF TIME

Ancient stone beneath the Arizona desert could answer long-standing questions about dinosaur evolution — and hint at our solar system's possible fate.

BY **DOUGLAS FOX**

Paul Olsen

A deep-bellied rumble reverberates through an expanse of tired, wrinkled badlands. A diesel truck sits atop a mesa, a metal shaft extending downward from the rear of its bed, piercing the earth like a stinger. The shaft spins 20 times per second. Hundreds of feet below, its diamond-crusted end grinds through layer after layer of sedimentary stone. The hard-hat workers running this rig often drill for gold or other valuable metals. But today they're drilling for something entirely different.

The workers idle the drill, and the roar abates. They hoist a cylinder from the hole, as long and skinny as a person's arm, and hurry it into a tent and onto a table. Hidden inside the muddy plastic cylinder is a section of core from a long-buried world. For stone, it is surprisingly fragile. The sheath protects it from swelling and crumbling.

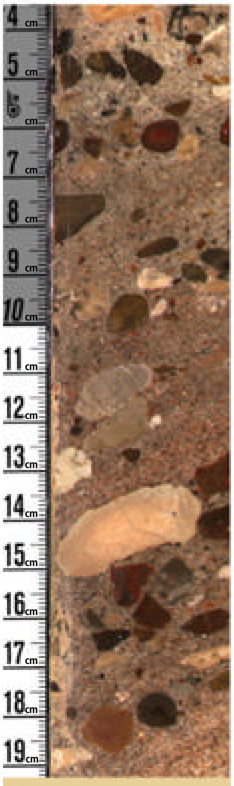
In Arizona's Painted Desert, paleontologist Paul Olsen is drilling into multihued rock layers more than 200 million years old in hopes of confirming his controversial timeline for the late Triassic period.

KEVIN KRAJICK/LAMONT-DOHERTY EARTH OBSERVATORY/COLUMBIA UNIVERSITY

Paleontologist Paul Olsen kneels for a look at the round cross-section of stone at the end of the core. It is bluish, cluttered with gray, oblong shapes.

All day and night for the past week, core sections have emerged from the drill hole every few minutes. Their blue, gray or reddish colors mirror the stone layers exposed on the surrounding badlands here in Arizona's Petrified Forest National Park. This landscape, comprising the so-called Chinle formation, coalesced from layers of mud and gravel laid down over 200 million years ago. Back then, this area was a land of tropical forests, floodplains, lakes and meandering rivers.

Olsen and his colleagues will study these cores for years to come. But even now, Olsen, with Columbia University's Lamont-Doherty Earth Observatory in Palisades, N.Y., can intuit something about how these ancient landscapes evolved. The reddish layers represent dry patches of ground where oxygen seeped into the soil and rusted the iron minerals in it. The blue-gray layers show where the drill penetrated the bed of an ancient lake or river; low oxygen levels prevented the iron minerals from rusting. Some cores even hold traces of ancient plant roots or animal burrows.



The large pebbles in this Triassic core from the Chinle formation in Arizona once tumbled down a fast-moving stream.

Inside this particular section of core, Olsen finds chicken egg-size river cobbles — evidence of a current "strong enough to move those pieces of rock," he says.

At 61 years old, Olsen is lean and rangy, with a Teddy Roosevelt mustache and wire-rim spectacles. For most of his life, he has studied the Triassic, which stretched 200 million to 250 million years ago and included the emergence of early dinosaurs. Now, working in Arizona, in one of the world's most enigmatic Triassic deposits, Olsen and his colleagues aim to reshuffle the rocky layers of history and transform our understanding of how dinosaurs came to dominate Earth.

During the Triassic, the world's continents were locked together in a single supercontinent called Pangaea, allowing animals to roam unimpeded by large bodies of water. But Olsen and others believe that for 30 million years after dinosaurs first appeared, they remained stranded, for the most part, in the geographic fringes of this world. They were confined by their own novel physiology, which differed from other reptiles and amphibians and limited where they could live. Not until after a catastrophic chain of volcanic eruptions cooled the Earth and decimated those competitors did dinosaurs become dominant worldwide. This idea is still "highly debated," Olsen admits. The Chinle coring project, he says, "hopefully will provide the linchpin" to confirm it.

The research team's coring drill, seen here at sunset, bores deep into Arizona's Painted Desert to extract ancient stone. By the end of the monthlong project, workers had drilled through 1,700 feet of rock.

A segment of core extracted from the Chinle formation. Olsen and his team are now analyzing these cores for clues about how dinosaurs evolved more than 200 million years ago during the late Triassic.

Stacked cores from the Chinle drilling project. The different colors show how the Triassic landscape changed over time due to shifts in climate.

But Olsen's interest in these rocks doesn't stop there. He's also investigating another mystery that is at once stranger, darker and more profound. Odd as it sounds, he plans to read the ancient, ephemeral motions of Mercury, Venus and Mars in those very same rocks — and test some fundamental assumptions about the cosmic clockwork that keeps our solar system's inner planets orbiting in perfect sync. If the suspicions of Olsen and a few other scientists are right, then unspeakable violence may lurk in our solar system's future — maybe even a premature end for Earth.

A MESSAGE FROM THE PAST

Olsen's journey into these questions began 45 years ago in the late 1960s, while he was a teenager growing up in Livingston, N.J., outside Newark. He and his friends spent entire days at an abandoned quarry, chiseling out reptile footprints and fish fossils. The quarry provided a window into changing Triassic climates: Layers of red sandstone, often containing footprints, represented times when the area was a muddy marsh. Interspersed in the red stone were narrow bands of black shale containing petrified fish, from a time when a deep lake covered the area. Olsen began searching beyond the quarry for petrified fish, always seeking out the black layers he knew would hold them.

Olsen looked for places where creeks had chewed away the soil, leaving the rock layers exposed. Walking along the banks, he scrutinized the red pebbles; a single shard of black among them would alert him to a shale layer somewhere upstream. The thin, black layers weren't too hard to find. They always occurred in the same curious pattern, against a background of red rock: first a single black layer, then two black layers close together, then three close together, then another three, then two. This whole sequence repeated over and over again, up and down the strata — a mysterious telegraph signal conveying some unknown message from the past. Olsen thought about it often.

He earned C's and D's in high school math and English, hindered by dyslexia and a lazy eye. But he possessed a knack for seeing patterns in the rock that seasoned geologists missed.

Olsen could predict where he would find the next batch of black strata, based on the tilt of the layers and the regular distances between them. Often it was dozens of miles away. When he turned 17, he bought a Chevy Blazer with help from his parents and followed his curiosity across Pennsylvania, Connecticut, Virginia and North Carolina. He found that these repeating layers — long thought to be local — actually extended across the region. He updated published geologic maps and sketched fossils that were new to science.

Those endeavors landed Olsen where his shabby grades never could have: at Yale, where he studied geology. Those repeating layers that captivated him as a teenager drew him into a lifelong career studying the Triassic.

The period intrigued Olsen because it was a time of great beginnings. "Everything that dominates the world now, all the major groups on land, originated in the Triassic," including frogs, salamanders, turtles, crocodiles, mammals and birds, says Olsen. And late in the Triassic, the first dinosaurs appeared.

Reconstructing those beginnings has proven difficult, though. Paleontologists sometimes build timelines from ancient ocean beds, where 100 million years of sediment layers are often stacked in one continuous sequence. But the Triassic is too old: Those pieces of oceanic crust have long since slid under the edges of continents and melted into magma. Paleontologists must instead assemble timelines from fragments, such as sediment layers from short-lived inland seas.

As a result, there is no agreed-upon timeline for the Triassic, no universal yardstick to compare the ages of Triassic fossils around the world. This means scientists can't agree about when, and in what order, various species appeared and vanished.

The red and black layers, Olsen believed, provided an opportunity to fill these gaps. In that region, called the Newark Basin, 5 miles of sediment layers spanning 32 million years had piled up in a sinking basin.

This Connecticut roadcut shows the layers of black rock in the Newark formation, which Olsen and his team used to create a Triassic timeline.

Olsen continued his modest studies of the region, bolstering his ideas before undertaking something large and expensive. By 1990, he finally had the funding to complete the mapping project he started as a teen. Rather than relying on exposed rocks, he drilled thousands of feet into the ground and extracted eight cores, from New Jersey, Pennsylvania and Connecticut comprising 26,700 feet of stacked layers. The Newark coring project confirmed the ideas that Olsen formulated as a teenager. The regularly stacked red and black layers showed up clearly in the cores: The pattern really did extend up and down the Atlantic coast. "It was breathtakingly exciting," he recalls.

Despite this success, Olsen still needed to determine the ages of the layers; scientists can date only certain types of rocks. He could extract only two ages from the 26,700 feet of core, from a pair of volcanic rock layers near the top.

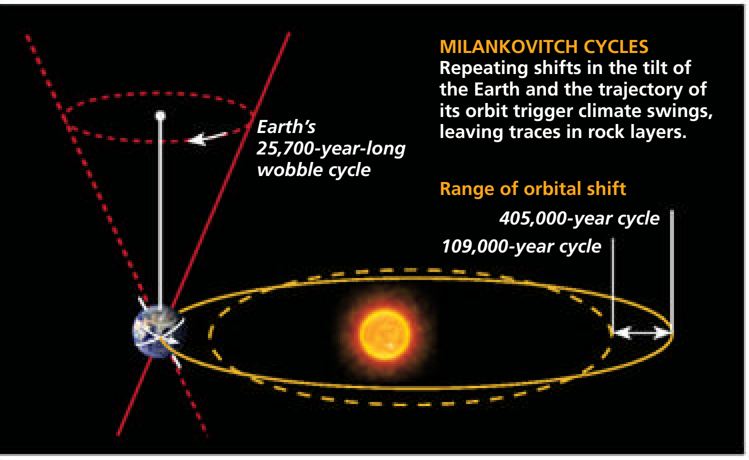
To circumvent this problem, Olsen turned to an experimental technique that would allow him to use those repeating red and black layers as markers of time. He recalled that Franklyn Van Houten, a Princeton scientist whom he met as a teenager, interpreted those dry and wet climate layers as evidence of something called Milankovitch cycles. In the 1960s, Van Houten and a few other scientists started

OPPOSITE, CLOCKWISE FROM LEFT: COLORADO PLATEAU CORING PROJECT; KEVIN KRAJICK/LAMONT-DOHERTY EARTH OBSERVATORY/COLUMBIA UNIVERSITY (2); COLORADO PLATEAU CORING PROJECT. THIS PAGE: COURTESY GILBERT N. HANSON

to believe that Earth gradually wobbles in a repeating pattern, affecting the planet's trajectory around the sun. These orbital cycles, which alter the intensity of sunlight arriving in summer and winter, were thought to trigger periodic climate swings (including ice ages) and changes in precipitation.

These climate shifts, the theory went, were caused by the combined effects of three cycles: A wobble in Earth's axis repeating every 25,700 years, on average, and orbital shifts repeating every 109,000 years and every 405,000 years, respectively. Based on his studies of exposed rock faces scattered around New Jersey, Van Houten believed he saw the 25,700-year wobble cycle imprinted in the Newark layers.

With 5 miles of cores in hand, Olsen looked again at those wet and dry climate layers to see if he could use those cycles as units of time. He was amazed to see that the 25,700-year,



MILANKOVITCH CYCLES
Repeating shifts in the tilt of the Earth and the trajectory of its orbit trigger climate swings, leaving traces in rock layers.

109,000-year and 405,000-year cycles overlaid clearly onto the relative thickness and spacing of the Newark layers, suggesting that the ancient climate swings recorded in them really were caused by Milankovitch cycles.

The idea of these climate-influencing cycles, once widely ridiculed, offered Olsen a much-needed tool. Starting with the dated lava layers at the top, he used the 405,000-year cycle — the one most clearly visible in the repeating layers — as a measuring stick to tick off a series of 405,000-year time increments down the rest of the core. This provided a way of knowing the age of any particular layer within it.

This timeline — combined with other methods, such as reading the magnetic "barcode" left in sediment by the periodic flip of Earth's magnetic poles — would provide the fine resolution of just a few thousand years that Olsen and his colleagues needed to compare the ages of fossils from around the world. Finally, they could get a clear picture of how dinosaurs first evolved and populated Earth.

Olsen and geologist Dennis Kent (also of Lamont-Doherty) published the new timeline, called the Newark astrochronology, in 1995. It contradicted some major assumptions about the Triassic world. Most paleontologists believed that any dinosaurs alive in the late Triassic would simultaneously inhabit all of Pangaea — a reasonable assumption, since the continents were melded into a single landmass stretching nearly from the North Pole to the South Pole, allowing animals to roam freely. But Newark showed something different.

Newark layers with very few dinosaur fossils lined up in age with deposits in Europe, India, southern Africa and South America that were littered with early dinosaurs called prosauropods, which would later spawn brontosaurs and other long-necked, four-legged beasts. This suggested that for 30 million years, while early dinosaurs thrived in some parts of Pangaea, only a few small-bodied species — none of them prosauropods — managed to gain a foothold in what became North America. "There has to be something ecological going on that just doesn't let these animals establish themselves" in that area of the world, says Olsen.

DUELING TIMELINES

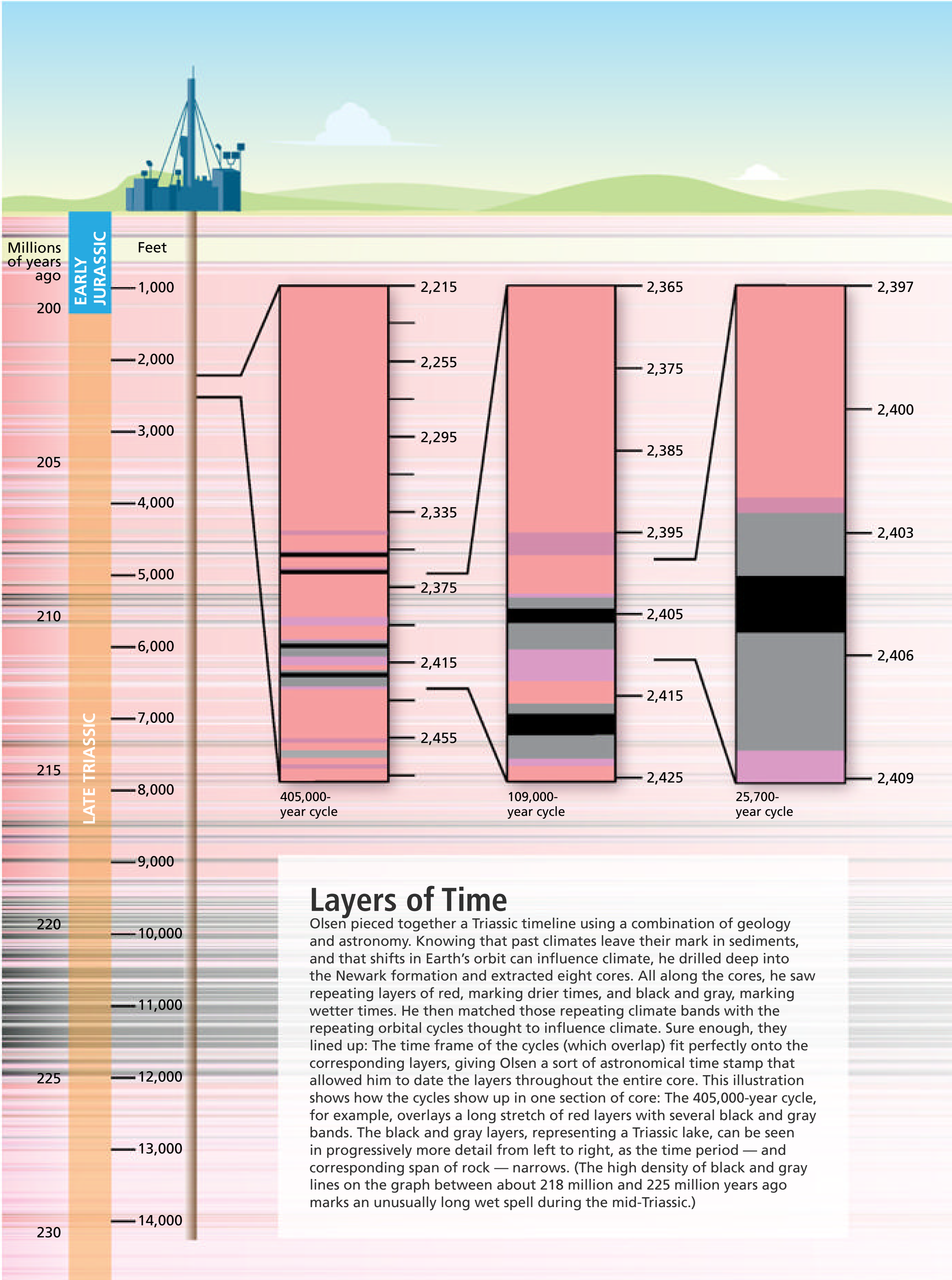
This emerging theory raises some startling questions about evolution. If you overlay Pangaea with the locations where his timeline says that dinosaurs did and didn't dominate in the late Triassic, a striking pattern emerges: Amphibians and crocodilian reptiles dominate the warm, equatorial regions where North America sat at the time, while dinosaurs and mammalian ancestors abound in cooler and wetter regions, north and south.

"That bears on the fundamental nature of what dinosaurs are and why they became dominant," says Olsen. Studies of skeletal anatomy and growth rates suggest dinosaurs may have been warm-blooded, allowing them to grow quickly. Randall Irmis, a paleontologist at the University of Utah who leads the Chinle drilling project, believes that for the most part, dinosaurs remained confined to that high-latitude niche for 30 million years after they first evolved; their larger size and rapid metabolism made it difficult for them to find food in the hot, seasonally dry climate of the equatorial regions.

Not until 201 million years ago did dinosaurs begin to dominate worldwide, say Olsen and Irmis — after a mass

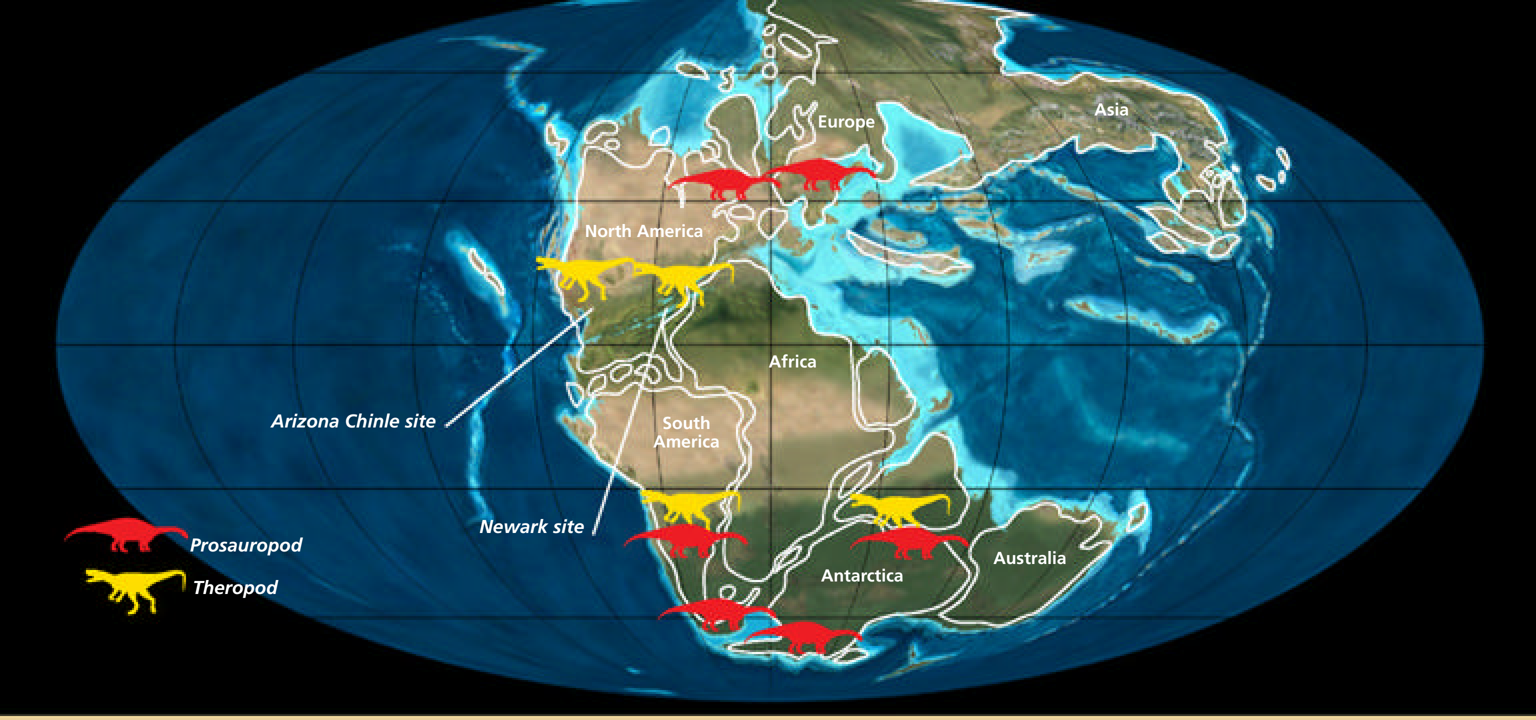
Scientists dispute the range of prosauropods, such as this Plateosaurus, during the Triassic.

PROSAUROPOD: SERGEY KRASOVSKIY/STOCKTREK IMAGES/CORBIS. ABOVE AND OPPOSITE: JAY SMITH



Layers of Time

Olsen pieced together a Triassic timeline using a combination of geology and astronomy. Knowing that past climates leave their mark in sediments, and that shifts in Earth's orbit can influence climate, he drilled deep into the Newark formation and extracted eight cores. All along the cores, he saw repeating layers of red, marking drier times, and black and gray, marking wetter times. He then matched those repeating climate bands with the repeating orbital cycles thought to influence climate. Sure enough, they lined up: The time frame of the cycles (which overlap) fit perfectly onto the corresponding layers, giving Olsen a sort of astronomical time stamp that allowed him to date the layers throughout the entire core. This illustration shows how the cycles show up in one section of core: The 405,000-year cycle, for example, overlays a long stretch of red layers with several black and gray bands. The black and gray layers, representing a Triassic lake, can be seen in progressively more detail from left to right, as the time period — and corresponding span of rock — narrows. (The high density of black and gray lines on the graph between about 218 million and 225 million years ago marks an unusually long wet spell during the mid-Triassic.)



A map of Pangaea during the late Triassic shows where evidence of prosauropod dinosaurs and theropod dinosaurs has been found. (Modern-day continents are outlined in white.) Under Olsen and other scientists' interpretation of the evidence, prosauropods remained confined to the higher, cooler latitudes for 30 million years after dinosaurs first appeared and became dominant only after volcanic eruptions wiped out many of their competitors.

extinction, caused by volcanic eruptions, wiped out many of their cold-blooded reptile and amphibian competitors. This would have been one of the greatest extinctions of all time. But Spencer Lucas, a former Yale schoolmate of Olsen's and now a renowned Triassic authority at the New Mexico Museum of Natural History, disputes its very existence. Lucas has spent 30 years assembling his own Triassic timeline using biostratigraphy. With this method, which uses specific types of fossils to determine the age of the layers that hold them, evolution itself becomes a marker of geologic time in the rocks. His fossil-based timeline shows only a series of smaller extinctions in the late Triassic.

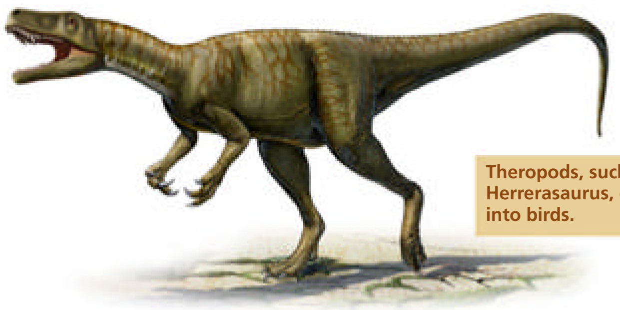
Lucas points out plenty of weaknesses in the Newark astrochronology. Its Triassic layers contain footprints that he and his colleagues attribute to prosauropod dinosaurs (an interpretation that Olsen and others dispute). He ridicules the reliance on only two firm rock ages. And he points out that using layer thickness to measure Milankovitch cycles requires a risky assumption: that the rate of sediment accumulation, which built these layers, did not change much over 32 million years. Most damningly, he believes the cores are riddled with unseen gaps where erosion periodically obliterated sediments, potentially throwing off the timeline by millions of years.

"It's an enormous scientific house of cards," he says. "What we need to do is kick that house over and move on."

Olsen remains undeterred by Lucas' skepticism. He believes the 1,600 feet of Chinle cores extracted from Arizona's high desert will confirm what he saw in Newark and settle the argument.

DRILLING FOR ANSWERS

The day after our chat at the drill site, Olsen drives down



Theropods, such as this Herrerasaurus, evolved into birds.

a winding road in the Petrified Forest, munching arugula and dried red chilies. When traveling, "I really try to skip meals," he says.

The gray and pink-striped badlands flitting past us represent one of the richest, yet hardest to understand, Triassic fossil deposits in the world. Layers in the Chinle formation, which stretches from West Texas to Nevada, are hard to trace horizontally due to faulting and tilting and because the types of rocks making up the layers change over small distances — a result of the heterogeneous landscape of forests, rivers, lakes and swamps that formed them.

Paleontologists have unearthed thousands of skeletons here. As with Newark, they include plenty of amphibians and crocodilian reptiles — even some small dinosaurs called theropods — but not a single prosauropod, say Olsen and Irmis. Lucas and his colleagues disagree. They interpret fossil footprints found in Chinle strata around the region as belonging to prosauropods. In Arizona, Lucas and his team have assembled the layers exposed across the park into a single combined sequence. They place the stack of layers between about 212 million and 225 million years old. That's in line with other fossil beds in Europe and South America that show prosauropod dinosaurs were gradually becoming larger and more common at that time.

Olsen and his collaborators, however, believe that Lucas'

TOP: RON BLAKEY/COLORADO PLATEAU GEOSYSTEMS. BOTTOM: SERGEY KRASOVSKIY/STOCKTREK IMAGES/CORBIS

footprint interpretations and age estimates are wrong. He prefers an alternative Chinle timeline constructed by William Parker, a National Park Service paleontologist. Parker claims to correct a major error in Lucas' timeline — the accidental omission of nearly 200 feet of strata. When Parker adds the omitted strata back into his timeline, the overall chronology changes: The upper layers of the Chinle formation are about 5 million years younger — no more than 207 million years old.

Parker's estimate, if correct, means those Chinle layers lacking prosauropods are young enough to align with strata from high-latitude areas of Pangaea where the fossil record shows prosauropods had become plentiful. This heightens the contrast between dinosaur populations at the high and low latitudes. And it's just what Irmis and Olsen would expect, since they believe prosauropods and other large dinosaurs thrived for 30 million years at high latitudes before managing to establish in the tropics after a mass extinction 201 million years ago.

Just before dusk, I walk with Olsen away from the roar of the drill site to the edge of the mesa. It overlooks a layer of petrified tree trunks, dusted white with ancient volcanic ash. Volcanoes often sprinkled ash here during the Triassic, and scientists can date that ash by counting uranium and lead atoms caged inside tiny, near-microscopic zircon crystals. The white layer below us has been dated at 210 million years, one of only a dozen or so hard dates obtained for the entire Petrified Forest. Olsen's collaborators will date thousands more zircons up and down the 1,600-foot core being drilled behind us.

"It would be nice if there's a smooth progression of ages down the hole," says Olsen. It would help them line up the Chinle and Newark cores and rebuff Lucas' criticisms. But ages in the core might also be scrambled, with older zircons layered above younger ones.

It is true in geology that rock equals time, but most rock is made of materials recycled from elsewhere on Earth. The badlands stretching out below Olsen and me originated from ancient mountain ranges in what are now Texas, California and Canada. Those mountains eroded, sending more than 1,000 cubic miles of sediment and older zircons tumbling down rivers and settling in the northern Arizona Chinle region over 200 million years ago, building the rocks we see here. Olsen's collaborators hope to sort out the zircon age problem by selectively dating ones with sharp rather than battered edges — those that came from the sky rather than a riverbed.

If the Chinle cores yield a coherent sequence of dates, and if they agree with the Newark timeline, they could also shed light on the past and future movements of planets in our solar system.

PLANETS IN MOTION

If the Chinle cores yield a coherent sequence of dates, and if they agree with the Newark timeline, they could also shed light on the past and future movements of planets in our solar system.

When Olsen studied his Newark cores in the mid-1990s, he noticed something odd. The Milankovitch cycles recorded in the rocks lined up well with those known in today's world, with one exception: A much longer cycle, marking a subtle gravitational tug-of-war between Mars and Earth, was off. Instead of 2.4 million years (as it is today), Olsen's cores showed the cycle lasted 1.75 million years. It was a hint that the movement of planets in our solar system hasn't always been what it is today.

When Olsen presented these results at a meeting in 1999, the man who followed him at the podium was visibly excited by what he had just seen. "That was exactly what I was proposing to do," he told the audience.

The man was Jacques Laskar, an astronomer at the Institute for Celestial Mechanics in Paris. He had spent a decade working on a 200-year-old problem: whether the planets' orbits are stable, or if they drift unpredictably over time.

Laskar's theoretical calculations for Mercury, Venus, Earth and Mars suggested the latter — that orbital deviations of just 50 feet will propagate to 240 million miles over 100 million years due to tiny shifts caused by gravitational tides in the planets' interiors and other factors. Now, Olsen had unexpectedly provided evidence that it could be true. The implications were breathtaking.

Laskar's analysis suggests that 1 billion to 3 billion years from now, Mercury could be tossed from its orbit, whereupon it might crash into the sun, slam into Venus or possibly even sling Mars onto a collision course with Earth, mashing our planet into a glob of molten rock.

The chances appear remote; Laskar's simulations show Mercury tossed from its orbit only 1 percent of the time. But other outcomes could still prove disastrous. Venus could go awry and crash into Mercury, unleashing millions of large fragments, some potentially colliding with Earth. And a near miss between Earth and Mars could cause much of the Martian crust to be ripped off by Earth's gravity, pulling thousands of meteors onto our planet.

This scary talk is speculative, but if the Chinle results match what Olsen and his team saw in Newark, those data on orbital variations could help Laskar better quantify the risk.

All of this remains a work in progress. The Chinle cores have already undergone CT scans to map their internal structure, and in February, Olsen and his colleagues began examining them in detail by eye — the first step in detecting evidence of Milankovitch cycles. Lucas, for his part, is surveying amphibian, crocodilian and dinosaur fossils found at over 800 sites across the western U.S. to refine his own timeline of when species appeared and vanished during the late Triassic.

Whichever timeline wins out — Olsen's or Lucas' — one thing is clear: Finding a way to measure deep time will shed light on all manner of questions from evolution to astronomy to eschatology, many of them not yet asked. D

***Douglas Fox** is a writer whose work has also appeared in* Scientific American, Esquire *and the* Christian Science Monitor.

FIGHTING THROUGH THE FOG

The trauma of a concussion left Clark Elliot struggling to reclaim his mind — and his life.

BY **CLARK ELLIOTT**
PHOTOGRAPHY BY **KEVIN MIYAZAKI/REDUX**

On Sept. 27, 1999, my world as I had known it for 43 years ended. I was sitting at a stoplight at the intersection of Oakton and Gross Point Road in Morton Grove, Ill., on my way to give a lecture at one of DePaul University's suburban campuses, waiting behind two other cars. A steady drizzle was falling.

Without warning, a Jeep skidded on the wet pavement and slammed into the back of my Mazda sedan. My head bounced off the headrest behind me and then was flung forward. I saw stars and blacked out for a second. I was groggy, but I pulled my car out of the busy intersection, drove around the corner and parked on the side of Gross Point Road. I felt shaken up, but only in the way anyone who had been in a relatively minor car crash might.

A Morton Grove police officer arrived to take the accident report, and I got out of my car to meet him.

"Get back in your car and sit there until the ambulance comes!" he said after he got a look at me. "I'm calling them now." This was puzzling to me. I couldn't understand why he was so concerned.

The ambulance came, and a pair of young paramedics, a small man and a large one, had me sit inside it as they examined me.

"Do you know your name?" asked the bigger one.

I thought about it. It seemed like an easy enough question. But nothing immediately came to mind. I was reaching into the usual place in my mind, and retrieving nothing at all. How odd, I thought. After a minute I managed, "Sure. Clark Elliott."

"Well, Mr. Elliott, I think you'd better come with us to get checked out at the hospital."

"Whoa!" I said. "I can't do that. I have to get to class."

"Listen, Mr. Elliott," said the smaller paramedic. "Pardon my expression, but you're pretty f---ed up here. We really need to take you to the hospital."

"Thank you for your concern," I said, smiling at him, "but I'm fine. I really can't go with you because I have to teach tonight."

I didn't hurt very much. I'd given a thousand lectures over 12 years without ever missing one. It would take a lot to make me miss class. My students were expecting me to show up shortly and teach for three hours. I felt strange, but I could not recall what it was like to not feel strange.

I couldn't make sense of what they wanted me to do. I couldn't see it in the normal way. So I refused to go to the hospital.

"OK," said the larger paramedic. "We can't stop you. You've got to sign these release forms, and then we'll let you go. But you are doing the wrong thing." I climbed out of the ambulance and went back to my car.

The back of my Mazda was all smashed in, but the car was still running fine. So I drove to work, mindlessly following the path I had taken many times before. Later that evening, I thought it odd that I could not remember a single thing about the rest of my drive to work. The details of my evening-class lecture were spotty, but I remember I worked on autopilot and lectured sitting down. There were difficult moments when I stopped midlecture and had to rest my head down on my desk. But DePaul's graduate students are a bright, multiethnic, salt-of-the-earth sort of crowd, and we joked about my loopiness being caused by the automobile accident. None of us took it seriously.

When I finally arrived home, it was hard for me to get up out of the car. It was hard for me to walk from the car to the house. I had a strange and persistent difficulty unlocking my front door. The next morning, I was still physically exhausted. I tried to get up and start my day, but I couldn't move. I was giving the command to my body: "Get up!" but it was not listening. Finally, after a long three minutes, once I was able to manage the smallest initiation of motion, I was able to stand up and move normally.

Over the next hour, I noticed several more instances of my being unable to initiate action. I brushed any concern aside, telling myself that my muscles had just been "shaken up" more than I realized the day before in the accident, and that since the muscles were sore and tired, it was hard to get

them to respond. It would take me four more days — and a puzzling episode where it took me six hours to realize that I had my shoes on the wrong feet — before I finally got myself to an emergency room for the diagnosis: a concussion.

CONCUSSION AND BALANCE

Unless you have experienced a concussion and lost efficacy in your balance system, you probably have no idea how devastating the effects of this can be in one's life. Because of inner-ear damage — yet another result of the crash — I had to deal with balance issues every day.

Roughly speaking, the balance system uses three overlapping components: the vestibular, or "inner ear," system, the visual system and proprioception, the feeling of our bodies in the space around us — a position-movement sensation. While the vestibular system is primary, the other two are also important, and the interaction among the three systems is far more complex than we generally consider.

Our vestibular and proprioceptive systems give direct information to our bodies to help them stay upright. But there is also a critical feedback loop between these two systems — processed in our brain stem — and our eyes.

The vestibulo-ocular reflex, for example, uses input from the brain's assessments of position and velocity to stabilize our gaze while we're moving. Our eyes adjust to stay fixed on an object the instant we move our head because the reflex makes microcontrolled adjustments in the extraocular muscles, causing the eyes to counter head and body movements. You can see this effect by looking directly at your own eyes in a mirror and moving your body around. In addition, these subsecond microadjustments are integrated with our ability to simultaneously adjust for the pursuit of objects moving in our environment as well, so we can turn our heads and bodies while still following the path of a bird flying across our yard. So our balance system controls our eyes.

But the relationship between our eyes and our balance system works in the other direction as well, and our eyes control our balance. When our vestibular system is underfunctioning — as often happens with head injury — our eyes can take over much of the load. We can illustrate this with a simple exercise: 1) Stand on one leg with your eyes open and your other knee up high; usually this is not too much of a problem. Notice the muscle adjustments in the foot that is on the floor. 2) Close your eyes, but continue to stand on the one leg. Depending on how effective your vestibular and proprioceptive systems are, you will experience varying degrees of increased difficulty when you lose the visual input (with a corresponding increase in the microadjustments in your foot). The more your balance depends on your vision, the more you'll start to wobble when you close your eyes.

> Whenever I walked around the university — where I had to think throughout the day — I would simply run an index finger along a wall as if I were goofing around. People tended not to notice this much, especially if I kept my hand low on the wall, and it was much better than looking drunk by weaving around in hallways and classrooms.

MOTION DISORIENTATION

Like many concussives, I had many episodes involving motion sickness that gave me trouble. For example, several weeks after the crash, I tried to take the elevated train downtown. Within a few stops, I felt so sick that I vomited in the train car and had to roll myself out through the doors onto a platform.

"I'm sorry!" I said to the variously disgusted and concerned passengers. "I don't know what happened. I'm sorry." It took me three hours to recover sufficiently before I could walk home.

On an evening almost a year later, I was exhausted from teaching class, and it was hard for me to walk — it took me an hour to get down the stairs of the classroom building. I didn't want to face walking up the stairs again in the building where my office was, so I talked myself into thinking it would be OK to take the elevator up to the sixth floor. This was a mistake. Once the elevator doors opened on six, I tumbled out onto the floor and crawled to the wall, where I could prop myself up. I rested there for 15 minutes, pretending to be sitting on the floor reading a book whenever students came by. Then I crawled to my office on my hands and knees and rested on the floor for an hour to recover my equilibrium.

My balance system is shot, and I have to rely on my eyes only, to know which way is up. The flood of data from my senses is overwhelming: the roar from the chain saw engine; the smell of oil burning on the muffler; the feel of branches pressing against me everywhere; sawdust, salty sweat and stinging two-stroke exhaust in my eyes and that I taste in my mouth.

BALANCE, VISION AND THOUGHT

Because I had suffered vestibular system damage, my already-overtaxed and poorly functioning visual system had to take on the extra load of providing for many of my balance needs. But at the same time, any sort of high-level thinking also required those same visual/spatial systems to create the internal *images* of thought.

Thus, we have the following: Under the cognitive load of thinking — which almost always entailed visualization, pattern matching and generating the spatial imagery to form analogies — my damaged brain would rapidly grow fatigued. The visual/spatial circuitry would get overloaded and could no longer manage its double duty making up for the vestibular system, and I would lose my balance. The same thing would happen when I had to use my visual/spatial circuitry to interpret meaning in complex sensory input — such as speech, or the complicated visual patterns on store shelves. One of the worst combinations would be when I had to use the visual systems in my brain simultaneously for both complex thinking, or sensory interpretation and intense balance calculations.

As my brain fatigue grew during even short periods of cognitive load, my balance would grow progressively worse, and nausea would almost immediately set in. Depending on what I was thinking about, or the physical task I was working on, I would start to lose my balance within five minutes.

I developed a surreptitious remedial balance technique: Whenever I walked around the university — where I had to think throughout the day — I would simply run an index finger along a wall as if I were goofing around. People tended not to notice this much, especially if I kept my hand low on the wall, and it was much better than looking drunk by weaving around in hallways and classrooms.

A neurological oddity that presented itself in my case, and one that you might notice in a concussive who is having balance problems, was that my index fingers would flex upward, with my thumbs out-thrust, while the rest of my fingers were relaxed downward, forming a flexed "L" between the thumb and index finger of each hand. If you put your arms out at slightly less than a 45-degree angle and raise your index fingers in this way, you will likely perceive this as a kind of balance-vigilant position.

WHERE THE BODY ENDS

Our balance systems are integrated with other important but little-considered systems as well. For example, a collection of nerves in the superior parietal lobe, roughly under the crown of the head, is thought to help us distinguish where the body ends and where the external world takes over. Without the capability to make this distinction, it would be difficult for us to navigate through a world filled alternately with

obstructions and openings through them. When brain activity in this area is naturally reduced — for example, when we drop off to sleep or fall into a deep meditative state — our sense of where the body ends is appropriately minimized.

This body-demarcation sense is taken for granted by people who haven't experienced a brain injury, but it can be quite troubling when it disappears unexpectedly. It is an interesting question to consider the relationships among the brain's visual cortex, our balance systems and this body-versus-surroundings demarcation sense. My experience suggests that there is a link. Under brain stress — primarily visual and especially when making excessive demands on my visual system for balance — the boundary line between my body and the rest of the world became blurry.

This was most easily noticed in my almost ubiquitous (though relatively mild) difficulty passing through doorways, going down tunnels (such as stairways and Jetways) and getting into cars when my brain was tired. I would have to put my arms out to "feel" the spatialness of the opening — using my eyes to carefully examine the distinctions between my hands and the surrounding objects — and thus guide myself through manually.

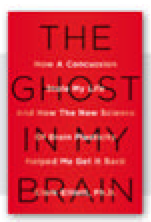
A more striking example of this loss of body-environment demarcation happened five years after the crash, as a result of a set of intense visual-balance demands.

One of the 50-foot trees in my backyard had Dutch elm disease, which can spread throughout a neighborhood, so it had to be cut down. High-ladder tree work of this kind is intense and not for the faint of heart. To set this in context, consider that a pair of supermacho day laborers who earlier had done heavy work on the foundation of my house showed up and said they would cut down the tree for a budget price. They laughed and taunted each other before climbing up the ladder to get to work, but each of them returned down after only a minute — with their knees uncontrollably shaking. They soon gave up and left. I couldn't afford to have it removed by other professionals, so in the end I had to manage it on my own.

I knew I would have to contend not only with the normal, rather striking visceral reactions of being so high up, but also with the added complications from my brain damage. The following diary passage is from a day when I had climbed 30 feet into the tree to cut off the highest branches, which themselves reached another 20 feet over my head. This episode simultaneously taxed my visual/spatial system for three separate tasks: the intense spatial planning of where the heavy tree branches were to be cut, and would fall; the meaningful interpretation of the incoming barrage of sensory input; and the essential need to keep my balance based primarily on the constantly moving visual input.

> *I am disoriented because I can't look down, and so have to get my visual bearings from watching parts of the tree, which are themselves swaying in the wind. It's all one chaotic swirl of sunlit green. My balance system is shot, and I have to rely on my eyes only, to know which way is up. The flood of data from my senses is overwhelming: the roar from the chain saw engine; the smell of oil burning on the muffler; the feel of branches pressing against me everywhere; sawdust, salty sweat and stinging two-stroke exhaust in my eyes and that I taste in my mouth. I am having difficulty managing the geometry of placing myself — my body, and the chain saw I'm holding — within the context of the moving tree. It's as though I've lost my sense of — the demarcation point of — the boundary between my inner self and the outer world around me. Except for what my eyes can tell me as I stare intently through the fog of my safety glasses at both my boot and the saw ripping through the branch on which that boot is standing, I have no way of distinguishing between the two. I have to manually, continually, walk myself through the connections in the branching of the tree, and the differential branching of my body. I can't tell the difference between them. Terrifying — given the circumstances, but also fascinating . . .*

It goes without saying that after I climbed down, I was unable to walk, or even stand up. Having to manage the chain saw without the natural protection of knowing where my body ended was intense, and the base fear this truly odd experience generated was extreme. It took me a week to get the tree down, and another two weeks after that before my brain recovered. **D**



Playing the Field

Thanks to Google Earth and other open-access imagery, amateur archaeologists are making spectacular finds — but what are we losing?

BY **GEMMA TARLACH**

On a wintry December day, in a farmer's barn tucked into the English countryside, Peter Welch was setting out snacks for fellow metal-detector enthusiasts when one of them came in and said, "You'd better have a look at this."

Welch tramped up a hill to where half a dozen people gathered around a freshly dug hole. In the cold ground was a handful of 11th-century coins, the first of more than 5,000 that would be found at the site as the excavation progressed. The discovery — one of the largest hoards of Saxon coins ever found in the United Kingdom — could be valued at more than $1.5 million.

For Welch, founder and owner of the Weekend Wanderers Detecting Club, the sheer thrill of the find was the proverbial pot of gold at the end of a rainbow called Google Earth.

The descendant of a CIA-funded project, Google Earth has become arguably the most popular — and ubiquitous — open-access satellite-imagery program in the world. Since its public launch in June 2005, Google Earth — with its virtual globe and street view capabilities — has found its way into driving directions, real estate presentations, study plans, online games such as GeoGuessr and flight simulators.

Google Earth has also revolutionized, for better and worse, amateur archaeology. In December 2014, for example, the same month Welch's group found the coin hoard, another amateur archaeologist used Google Earth to locate a Bronze Age burial site in the eastern English county of Suffolk. Two months earlier, an enthusiast in southwestern England discovered still another Bronze Age site, possibly a farm, after scouring satellite images online.

"It's invaluable. I can't imagine anyone not using it," says Welch.

PAST MEETS PRESENT

Welch became interested in the general area where the hoard was discovered, in Buckinghamshire, northwest of London, after finding a reference to a nearby estate in the famous 11th-century land survey known as the *Domesday Book*. Welch then used the famous 21st-century satellite imagery of Google Earth to hunt for specific spots that might be worth exploring.

"On Google Earth, you can see ridge and furrow quite clearly," says Welch, referring to a medieval method of plowing that leaves behind a distinct

One of the largest Saxon coin hoards ever discovered (top) was found in December 2014 by amateur archaeologists scouring a field in the English countryside using metal detectors. The field (middle) first attracted the interest of metal detector enthusiast and event organizer Peter Welch (bottom) through Google Earth satellite imagery of the location, which clearly showed a ridge and furrow pattern indicative of medieval-era plowing.

FROM TOP: PORTABLE ANTIQUITIES SCHEME; GETMAPPING PLC/GOOGLE EARTH; COURTESY PETER WELCH

land pattern even after centuries. "But it was a strange shape in the hedge line, a piece of woodland, that made me ask, 'Why is that there?'"

Before the days of the backhoe, if farmers hit a piece of masonry, buried boulder or another obstacle while plowing, it was easier for them simply to plant trees — a cue to avoid the spot — rather than dig up the object or keep snagging their plows, Welch explains. That's why a Google Earth image showing trees in fields that have been farmed for centuries draws the eye of enthusiasts like Welch, who makes his living identifying potential sites and organizing paid events to explore them further, at ground level.

Welch's enterprise has found numerous artifacts over the years, from Roman villas to Bronze Age beads. He obtains permission from landowners beforehand — Welch says he's found most landowners are curious about their properties' past but lack the time or manpower to explore often huge tracts of land. Outside of pheasant and partridge season, when they can make money by allowing hunting parties on their property, most of the landowners are happy to have Welch's group do the dirty work, literally, even though the landowners themselves will get little more than bragging rights over any treasures found.

Welch works with a liaison from the local county archaeologist's office to ensure any finds are properly documented and analyzed. For example, the Saxon coin hoard is now at the British Museum.

"I'm not a treasure hunter," Welch says. He notes that he and Weekend Wanderers have been involved in — and compliant with — the U.K's Portable Antiquities Scheme from its start in the late '90s. The program connects enthusiasts with professionals to encourage protection of sites as well as artifacts. In the Google Earth era, it's needed more than ever.

EYE IN THE SKY

Working archaeologists agree with Welch that Google Earth and similar open-access apps such as Flash Earth have changed how enthusiasts find sites. But the high-resolution imagery is not a revolution for the professionals; it's just the latest iteration of a tool that was around decades before the first satellite launched into orbit.

"Aerial photography, interpretation and mapping made the 20th century's greatest contribution to British archaeology," notes Ben Robinson, English Heritage's principal adviser for heritage at risk in the East Midlands region and host of the BBC show *The Flying Archaeologist*.

Aerial photography was equally important on this side of the Atlantic, says Francis McManamon, professor and executive director of the Center for Digital Antiquity at Arizona State University. Consider northeastern Louisiana's Poverty Point, for example, a mound complex that was a thriving city more than three millennia ago. Named a UNESCO World Heritage Site in 2014, Poverty Point was first surveyed by archaeologists in 1913.

Early 20th-century aerial photography provided the first views showing the scale of Louisiana's Poverty Point mound complex.

UNITED STATES ARMY CORPS OF ENGINEERS VIA WIKIMEDIA

"There's a big mound in the middle that's in the shape of a bird," says McManamon. People knew the mound was there but had no idea of its shape until 1938, when the Army Corps of Engineers flew over and photographed it. Even then, the files languished until 1952 before someone analyzed them.

Even though satellite imagery produces higher resolution, it has the same limitation as its predecessor.

BEYOND GOOGLE

Google Earth is not the only online destination for those who want the thrill of discovery without the dust and cramped tents of an actual field dig. Open-access satellite imagery sites and databases make it easy for enthusiasts to poke around archives and squint at shadows in the landscape.

BRITAIN FROM ABOVE
Registered users can help identify and classify more than 96,000 aerial images of England and Wales from the first half of the 20th century in this ongoing crowdsourced project.
→ *britainfromabove.org.uk*

THE DIGITAL ARCHAEOLOGICAL RECORD
Geared for researchers but accessible to the public, the online archive holds thousands of documents and other files on sites around the world.
→ *tdar.org*

FLASH EARTH
Zoom in on a spot and toggle between eight different image and mapping options from NASA, ArcGIS and other imagery collection sites. → *flashearth.com*

GEOGUESSR
By mixing Google Earth with road trip snapshots, the Swedish team behind this viral sensation have created a number of free and addictive games testing your knowledge of geography, topography and language — including one on famous places.
→ *geoguessr.com*

PORTABLE ANTIQUITIES SCHEME
Covering much of England and Wales, this database of discoveries from the government project promotes responsible amateur archaeology. → *finds.org.uk*

"Satellite imagery is still a photo. You'll only see what the eye can detect," says McManamon.

Professional archaeologists will still consult satellite imagery, especially for logistical planning of a field site. But when prospecting for new finds, they're more likely to use tools such as hyperspectral imagery, which can find electromagnetic fingerprints of objects and land features invisible to the naked eye, or light detection and ranging (LIDAR) technology, which maps subtle surface variations with extreme accuracy.

That means Google Earth and similar sites are used mostly by non-professionals. When asked if he looks askance at these amateur archaeologists, McManamon doesn't mince words.

"*Askance* is a generous term. *Horrified* is more to the point," he says.

In some fields other than archaeology, McManamon explains, amateur discoveries can be a boon to researchers short on time and funding for fieldwork. "With meteorites, the meteorite is the object," McManamon says. "Archaeology isn't like that. Most archaeological data is contextual. It's important to know what was found next to what, in which layer [of soil]. It's what happens at a site *after* the discovery of an artifact that's crucial."

English Heritage's Robinson agrees, noting context can be lost due to ignorance of, or indifference to, proper excavation methods. "Sadly, there is a persistent menace from those who deliberately set out to loot protected archaeological sites, or who couldn't care less about wrecking them," he says.

Although professional archaeologists lament the carelessness — and cluelessness — of many amateurs, they admit that Google Earth has boosted interest in their work. As more would-be Indiana Joneses take to the field with their smartphones and metal detectors, professionals are amping up public outreach programs to promote responsible exploration.

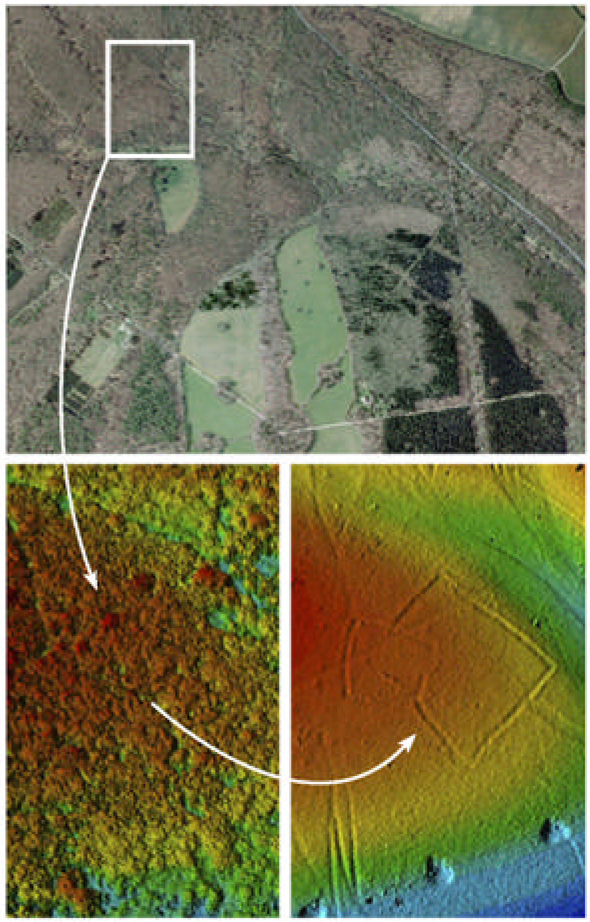
The U.S. doesn't have an online hub quite as comprehensive as the U.K.'s Portable Antiquities Scheme, but there are programs throughout the country, usually at the state level, that can help enthusiasts understand local and federal laws regarding trespassing and site protection — and what to do if a chance shadow you spot on Google Earth leads to an actual find.

"Take a photo, get precise GPS coordinates, but then take that information to the state archaeologist's office," advises McManamon. "You can still have the excitement of exploration and discovery, of getting out there, but ensure what you find gets properly preserved and interpreted."

McManamon and colleagues are also expanding the Digital Archaeological Record (tDAR), an online archive geared toward researchers but open to everyone.

"We get a lot of non-professionals using it, which we're thrilled about. I think access to archaeological records makes people better informed and, ultimately, better stewards of these sites, which are precious and non-renewable resources," says McManamon.

"Just don't pick anything up," he adds with a chuckle.



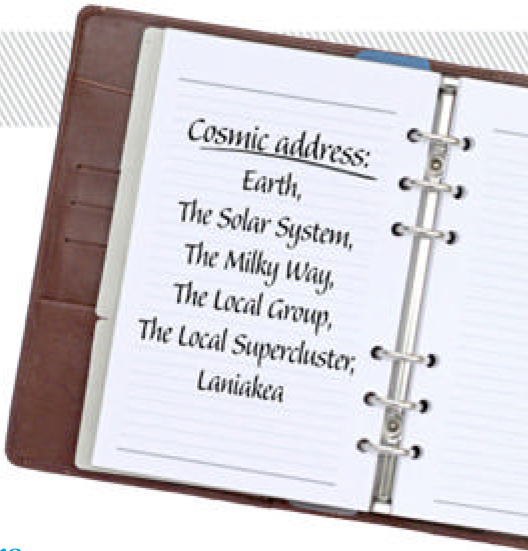
Three views of a site in England's Savernake Forest demonstrate satellite imagery's shortcomings (top). A LIDAR image (bottom left) shows fine gradations in elevation and, after processed to remove vegetation, reveals Iron Age construction (bottom right).

FROM TOP: INFOTERRA LTD AND BLUESKY/GETMAPPING PLC/GOOGLE EARTH; ENGLISH HERITAGE/CAMBRIDGE UNIVERSITY UNIT FOR LANDSCAPE MODELLING (2)

While armchair archaeologists rely increasingly on digital technology — be it Google Earth or other data sets — it's likely that a very human element will remain a key part of the discovery process.

Says Weekend Wanderer Welch: "For me, the biggest thrill is finding something with a tangible link to a person's life, like a lead seal matrix that's not worth much but might have his name and even his profession on it. To hold something that no one else has held since that person, to have that link to the past, makes it all worth it." D

***Gemma Tarlach**, senior associate editor at* Discover*, plays far too much GeoGuessr.*



Your Place in Space

Astronomers map out the biggest structure in the universe and offer a whole new way to think about "you are here."

BY **COREY S. POWELL**

Chances are, you've never met Brent Tully, and yet he knows exactly where you live. Better than you do, in fact — and probably better than anybody else in the world. Working at the University of Hawaii's Institute for Astronomy, he has spent decades researching the locations and distributions of galaxies across deep space. Oh sure, if you just want your location in a city, your phone's GPS can do that. But if you want to find your address in the universe as a whole, Tully is your go-to guy.

In terms of what he does and why he does it, Tully falls in with a long line of cartographers who've helped to make sense of the world and our place in it. But rather than filling in the terra incognita of our planet, he's plotting the lay of the cosmic land, sketching oceans of empty space and the shorelines of vast superclusters of galaxies.

Tully teased some of his latest findings two years ago at a conference in Marseille, France, held partly in honor of his 70th birthday. Then last September, he and his colleagues published a paper in *Nature* that unveiled their completed masterwork, a map of a single cosmic structure at least 500 million light-years in diameter. It contains about 100 quadrillion times the mass of the sun, equivalent to 100,000 Milky Ways. If you put the size of the structure in miles, it would be a 3 followed by 21 zeroes. It's big.

With this latest discovery, researchers have come closer than ever to defining humanity's place within the heavens.

Tully and company propose calling this greatest-known cosmic feature "Laniakea," from the native Hawaiian words meaning "immeasurable heaven." The name is evocative yet strangely ironic. Laniakea *is* measurable, and with this latest discovery, researchers have come closer than ever to defining humanity's true place within the heavens.


Brent Tully, atop Mauna Kea in Hawaii, maps our galaxy's whereabouts in the cosmos.

PUTTING STARS IN THEIR PLACES

The philosophical inspiration behind Tully's cosmic cartography comes from a multitude of mapmakers, but the scientific inspiration can be traced back to a single person: German astronomer and mathematician Friedrich Bessel.

In 1838, Bessel observed the apparent back-and-forth movement of the star 61 Cygni that results from our shifting perspective as Earth orbits the sun, an effect known as parallax. The movement was tiny — just 1/100,000th of a degree. (For comparison, the full moon spans half a degree.) But it was enough for Bessel to deduce correctly that 61 Cygni is about 10 light-years away. For the first time in history, humans knew the stars not just as points on a sky chart but as objects with defined locations in three-dimensional space.

Bessel's approach was far too limited to reach beyond our immediate galactic neighborhood, much less to the cosmic scales that Tully reckons, but it provided the crucial first step. Parallax made it possible to quantify the distances to the closest Cepheid variables, stars whose brightness varies

TOP: DRPNNCPP/THINKSTOCK/ALISON MACKEY/DISCOVER. BOTTOM: STEPHANE COURTEAU

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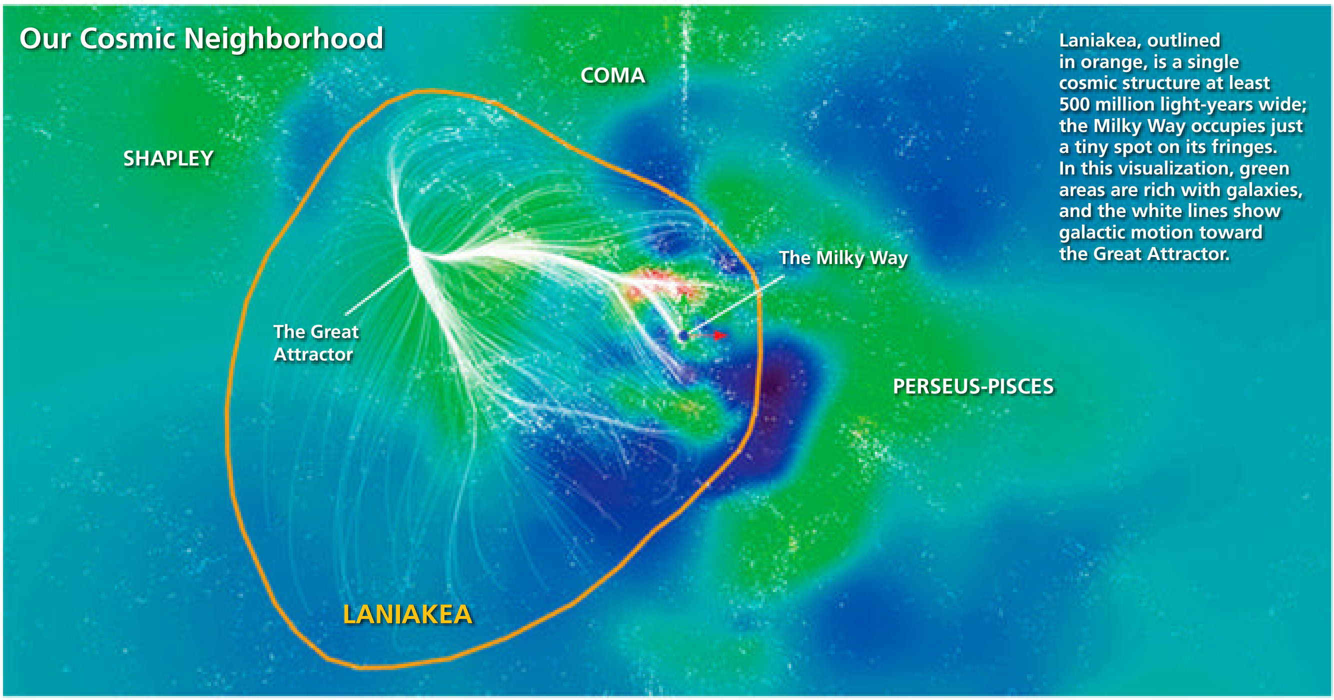


regularly over time. That period of variation is directly related to their true luminosity, so if you measure the period, you'll know the luminosity. Compare that with the apparent brightness and you know the distance, even at larger scales where parallax measurements are impossible.

Starting in 1914, American astronomer Harlow Shapley exploited the Cepheids to derive the overall shape of the Milky Way, and to show that we are in the outskirts of our galaxy, far from the crowded core of stars at the center. A decade later, Shapley's rival Edwin Hubble pushed the same technique much further and measured the distance to what was then known as the Andromeda Nebula, showing that it is actually a full-fledged galaxy far outside our own. Hubble then discovered the expansion of the universe, cementing his scientific fame and forever eclipsing Shapley.

It is worth pausing to consider how far the art of cosmic cartography has come. Less than a century ago, nobody knew if other galaxies even existed.

It is worth pausing to consider how far the art of cosmic cartography has come.

Now Tully and his cohorts are treating entire galaxies as mere coordinate points on a map of superclusters — that is, clusters of clusters of galaxies — that extends more than 200 times the distance to Andromeda.

The path to Laniakea required combining Cepheid measurements with five other forms of surveying tools, overlapping the data on top of each other to reach out to greater and greater distances. Tully himself is largely responsible for one of the key techniques he used, the Tully-Fisher relation, which links a galaxy's rotation speed to its intrinsic luminosity. Then, as with the Cepheids, he could compare that luminosity with the galaxy's apparent brightness to figure out its true place in deep space.

THE COSMIC BOONDOCKS ...
Identifying the locations of galaxies is only one aspect of creating a meaningful map, however. While Tully and his colleagues were surveying Laniakea, they also developed a novel way to designate landmarks. On Earth, it is easy to mark your location against familiar objects like rivers and mountain ranges. Space, it turns out, has its own markers.

By analogy with the way water flows on Earth, Tully looked at what he calls "watersheds" in space. He and his team measured the velocity of each galaxy, separated from the overall expansion of the universe. They ended up with a map of local galactic motions.

Just as water from the middle third of the contiguous United States flows toward the Mississippi River, Tully found that galaxies across about 500 million light-years of space flow toward a previously discovered enormous and dense region known as the Great Attractor because of its powerful gravitational pull. Tully describes it as "downtown Laniakea."

R. BRENT TULLY (U. HAWAII), ET AL., SDVISION, DANIEL POMAREDE, CEA/SACLAY

The new picture amplifies Shapley's humbling realization of a century earlier. Our Milky Way belongs to a meager gathering of about 54 galaxies called the Local Group. The Local Group lies on the outskirts of a much greater clumping of galaxies called the Local Supercluster, which collectively are on the fringes of Laniakea. If the Great Attractor is downtown, we are truly in the cosmic boondocks.

... OR THE CENTER OF THE ACTION?

Such grand pronouncements can still sound awfully abstract, and Tully is working to change that. "My moment of epiphany came 20 years ago when I was in a CAVE [a virtual reality room with images projected onto the walls] at the supercomputer center in Illinois," he says. "I could stride across the Local Supercluster in a few steps. Suddenly, I felt like these galaxies really exist there. This is reality, just on a scale that's generally inaccessible. We'd like to end up with a digital atlas that helps inform the public — as well as my colleagues, as well as myself — about where we live." You can find Tully's early, rough attempts on his homepage (www.ifa.hawaii.edu/~tully).

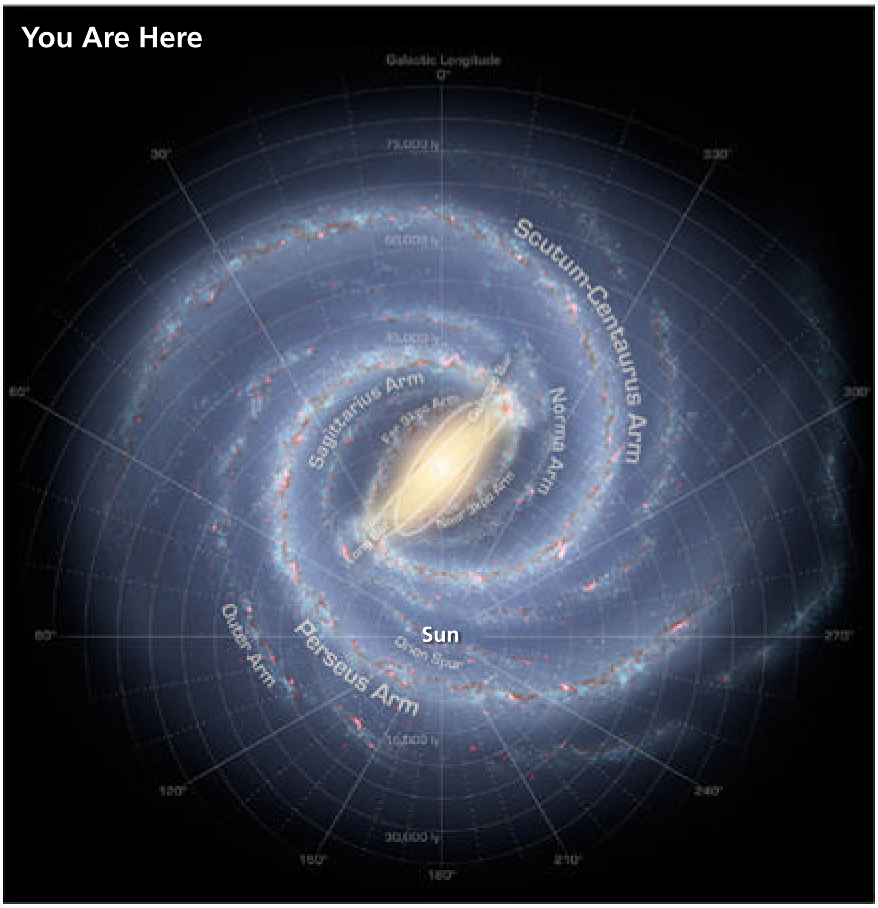
Scientifically, the discovery of Laniakea already feels very real. It bolsters theories of dark matter, since there must be significant unseen mass out there to account for the supercluster's pull. It also tests theories of cosmic origins, since observations of the background radiation from the Big Bang indicate that structures bigger than Laniakea should not exist.

But beyond downtown Laniakea, Tully has begun mapping out an even greater concentration of galaxies called the Shapley Concentration. (It seems Harlow Shapley, who recognized an overabundance of galaxies in that direction but lacked the tools to understand its true nature, finally got his due.)

"I don't think the story is going to be close to well understood until our maps are encompassing the whole domain around the Shapley Concentration," Tully says. That will require maps going out to over a billion light-years. "It's a huge job, but doable on a time-scale of decades," he says cheerfully. The Shapley Concentration is so huge and massive that it is yanking all of Laniakea, and us with it, toward the southern-sky constellation Centaurus.

Such large-scale motions have giddy, ego-testing implications. On the one hand, we are all traveling with Laniakea's gravitational flow, our fate dictated by the combined pull of thousands of faraway galaxies. But if you look at the very biggest picture, our place in the universe is defined by the Big Bang, an equal expansion of space in all directions. That's why, on the largest scales, all galaxies seem to be moving away from each other: Every location not only looks like the center of the expansion, in a meaningful sense, it truly is.

You can picture the place where you live as the outer arm of a spiral galaxy, in a remote region of the Local Supercluster, in the boondocks of Laniakea. Then again, you also can, with equal accuracy, picture a universe unfolding around you. The center of expansion — the center of the universe, really — is located exactly where you are sitting right now. **D**



Our solar system sits on a minor spur off an outer arm of our home galaxy, the Milky Way.

***Corey S. Powell**, editor at large of* Discover, *also writes the magazine's Out There blog. Follow him on Twitter,* **@coreyspowell**

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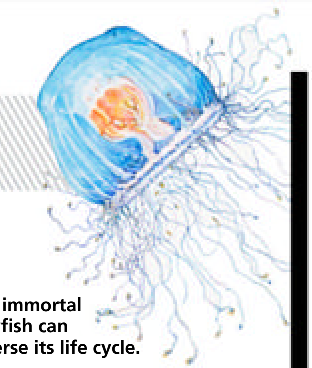
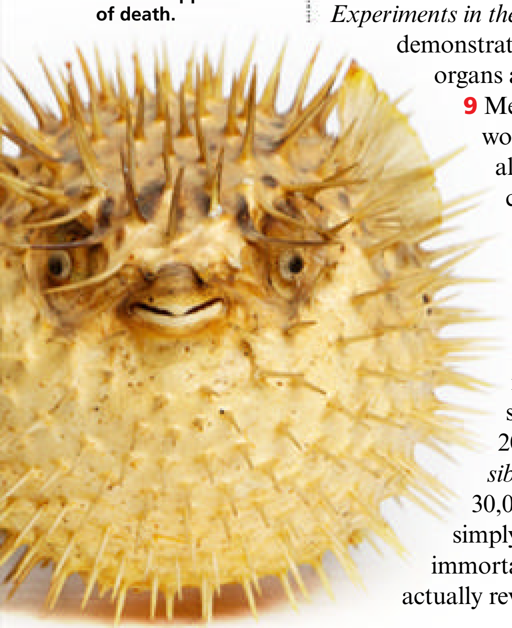
Immortality

BY GRACE HALDEN



The immortal jellyfish can reverse its life cycle.

1 Two things are certain in this world: We are born, and we die. But must we? Billionaire Dmitry Itskov and his group the 2045 Initiative want to cheat death by creating artificial bodies to house human intelligence. **2** Itskov and friends think they can develop a hologram "avatar," housing an individual's personality in an artificial brain, within three decades. **3** Terasem's LifeNaut project claims to offer longevity today. All you need to do is create a LifeNaut account and upload as much information about yourself as possible. Apparently the "mindfile" may be used to reconstruct you in the future. **4** Immortality isn't merely a 21st-century quest. In the third century B.C., Chinese Emperor Qin Shi Huang ingested mercury to gain eternal life. It didn't work. **5** We don't know if anyone tried to resurrect Qin, but in the 1980s, anthropologist and ethnobotanist Wade Davis documented cases of the "dead" rising from their graves in Haiti. **6** Davis claimed that by ingesting tetrodotoxin, a neurotoxin in pufferfish and other species, the living *appeared* to be deceased and could later be "resurrected." **7** Reviving the dead for real was a focus of the Soviet Union's Institute of Experimental Physiology and Therapy, overseen by Sergei Bryukhonenko. **8** The 1940 video *Experiments in the Revival of Organisms* supposedly demonstrated the institute's reanimation of organs and even decapitated dog heads. **9** Meanwhile, on the other side of the world, aviator Charles Lindbergh, along with scientist Alexis Carrel, conceived of many inventions and procedures to extend human life, such as an artificial heart perfusion pump. Lindbergh died of cancer in 1974. **10** While we humans obsess about achieving immortality, other organisms seem to do it effortlessly. In 2014, scientists revived *Pithovirus sibericum*, a virus preserved for 30,000 years in Siberian permafrost, simply by letting it thaw. **11** The immortal jellyfish (*Turritopsis dohrnii*) actually reverses its life cycle. An adult transforms itself through transdifferentiation — converting one type of cell into another — back into a juvenile form. **12** Members of another "immortal" species, the tiny invertebrate Bdelloid rotifers, are all female and reproduce by spawning identical clone daughters. **13** Scientists have been taking a cue from the little rotifers and cloning mammals for nearly 20 years, beginning in 1996 with Dolly the sheep, created by Ian Wilmut's team at the Roslin Institute in Edinburgh. **14** Dolly developed age-related conditions early and died at age 6; sheep often live to 12. Researchers found she had prematurely shortened telomeres, protective caps on the ends of chromosomes that reduce with age. **15** Although Dolly ignited an ethical debate about cloning animals, the practice has grown and gone commercial: South Korea's Sooam Biotech regularly clones pets for about $100,000.**16** Human reproductive cloning is widely prohibited, but therapeutic cloning — creating stem cells that are a genetic match to the patient — is more generally accepted because the cells are used to treat disease. **17** Unlike most other types of cells, which are programmed to die after a certain number of divisions, stem cells are immortal because they can multiply infinitely. Unfortunately, so can cancer cells. **18** The most famous case of cancer-based immortality is that of Henrietta Lacks, who died of cervical cancer in 1951. Cells from her malignancy were cultured and used to start a cell line, called HeLa, which lives on to this day in research labs around the world. **19** HeLa cell-based research has been instrumental in developing vaccines and fighting AIDS and cancer, but it has not been without controversy. No one informed or obtained consent from Lacks or her family to culture her cells. **20** Only in 2013, more than 60 years after her death, did the National Institutes of Health and Lacks' descendants agree how her cells and genetic information would be used. The arrangement establishes a precedent in cell line research ethics, granting Lacks a new legacy — itself a kind of immortality. D



In the right dose, tetrodotoxin, a neurotoxin in pufferfish, can cause temporary paralysis and the appearance of death.

*London-based cultural historian **Grace Halden** agrees with Freddie Mercury: Who wants to live forever, anyway?*

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